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Isolated IGBT Gate-Drive Push-Pull Power Supply with 4 Outputs

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Design Resources

TIDA-00181	Tool Folder Containing Design Files
C2000 LaunchPAD™	Tools Folder
LP2954A	Product Folder
TPS7A3001	Product Folder
LM5030	Product Folder
ISO5500EVM User's Guide	User's Guide
EE|Times	Power Tip #6: Accurately Measuring Power Supply Ripple

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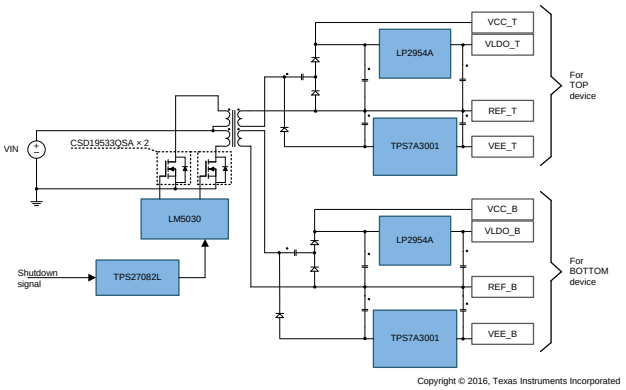
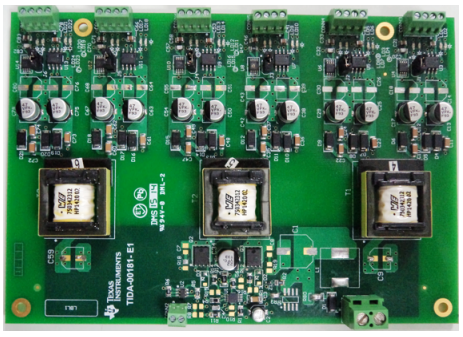
Design Features

- Isolated Power Supply for IGBT Gate Drive
- Supports 6 IGBT Gate Drivers for 3 Arms of Inverter (Each Arm in Half-Bridge Configuration)
- Push-Pull Topology Allows for Parallel Transformer Stages from a Single Controller for 3-Phase Power
- Two Isolated Outputs for Each IGBT: 16 V (x2) and –8 V (x2)
- Operates with Pre-Regulated 24-V Input
- Output Power: 2W/IGBT
- Scalable to Support Higher Power IGBTs
- Option to Shut Down the Power Supply to Facilitate Safe Torque Off (STO) feature
- Output ripple: < 200 mV
- Output Capacitors Rated to Support up to 6 A Peak Gate Drive Current
- Designed to comply with IEC61800-5
- Design Validated with TI's Isolated Gate-Driver ISO5500 Driving IGBT

Featured Applications

- Variable Speed AC/DC Drives
- Industrial Inverters and Solar Inverters
- UPS Systems
- Servo Drives
- IGBT-Based HVDC systems





1 System Description

This reference design provides isolated positive and negative voltage rails required for Insulated Gate Bipolar Transistor (IGBT) gate drivers from a single 24-volt DC input supply. IGBTs are used in three-phase inverters for variable-frequency drives to control the speed of AC motors. This reference design uses a push-pull isolated-control topology and provides isolation compliant to IEC61800-5. This reference design is intended to operate from a pre-regulated 24-V DC input. With a regulated (within 5%) input source, a simple open-loop, free-running oscillator can be implemented with a push-pull PWM controller.

The topology is essentially a forward converter with two primary windings used to create a dual-drive winding. This topology fully utilizes the transformer core's magnetizing current more efficiently than flyback or forward topologies. Another advantage this configuration has over flyback and forward configurations is that the supply output can be scaled up for higher power drives.

This reference design also takes advantage of another benefit of the push-pull topology in that multiple transformers can be controlled in parallel from a single controller to generate all the isolated voltage rails required for 3-phase IGBT inverters. Finally, larger IGBTs for higher power drives sometimes require more gate drive current than what is provided by a typical IGBT gate driver. For larger IGBTs, designers often use additional transistors for gate current boosting. This reference design provides 16 V on the positive outputs and –8 V on the negative outputs to compensate for the added voltage drop in these additional transistors.

Three-phase inverters are used for variable-frequency drives that control the speed of AC motors, and for high-power applications like high-voltage DC (HVDC) power transmission. A typical application of a three-phase inverter using six isolated gate drivers is shown in Figure 1. Note that each phase uses a high-side and a low-side IGBT switch to apply positive and negative high-voltage DC pulses to the motor coils in an alternating mode.

High-Power IGBTs require isolated gate drivers to control their operations. A single, isolated gate driver drives each IGBT that galvanically isolates the high-voltage output from the low-voltage controlled inputs. The emitter of the top IGBT floats, which requires use of an isolated gate-driver. In order to isolate the high-voltage circuit with a low-voltage control circuit, isolated gate-drivers are used to control the bottom IGBTs.

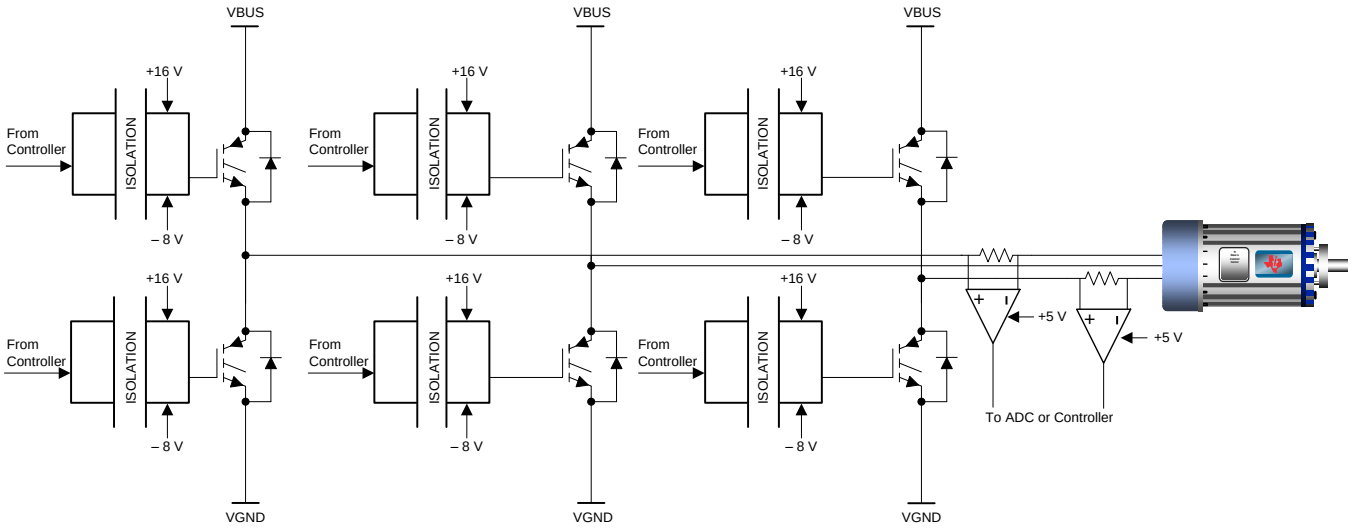


Figure 1. 3-Phase Inverter with Isolated Gate-Drive

1.1 Gate-Drive Supply Requirements

To reduce conduction losses, the gates of the IGBTs are supplied with a much higher voltage than the actual gate-threshold voltages. Typically, 15 V to 18 V is applied at the gate to reduce $V_{CE(on)}$.

The IGBT is a minority-carrier device with high input impedance and the capacity to carry a large, bipolar current. The switching characteristics of an IGBT are similar to that of a power MOSFET. Assuming identical conditions, IGBTs and MOSFETs behave identically when turned on, and both have similar current rise and voltage fall times. However, the waveforms of the switched current are different at turn-off.

At the end of the switching event, the IGBT has a “tail current”, which does not exist for the MOSFET. This tail is caused by minority carriers trapped in the “base” of the bipolar output section of the IGBT, which causes the device to remain turned on. Unlike a bipolar transistor, it is not possible to extract these carriers to speed up switching, since there is no external connection to the base. Therefore, the device remains turned on until the carriers recombine.

This "tail current" increases the turn-off losses and requires an increase in the dead-time between the conduction of two devices in a half-bridge circuit. To reduce the turn-off time, it helps to have a negative voltage (–5 V to –10 V) at the gate.

When an IGBT is turned on, some voltage spikes are generated on the gate terminal, due to the high dv/dt and parasitic capacitance between the gate and emitter. The voltage spiked can cause a false turn-on for the bottom IGBT. A negative voltage at the gate helps to avoid this false turn-on trigger.

Usually 16 V is applied to the gate for turn-on and –8 V is applied for turn-off.

It is important to decide on the power requirement to drive the IGBT. The calculation of gate drive power requirement for different power ratings of variable speed drives is explained in Equation 1.

As noted earlier, an isolated gate driver is used to turn the IGBT on and off. In this process, power is dissipated by the driver IC, IGBT gate, and by any RC circuits in the gate drive path. Refer to Figure 2.

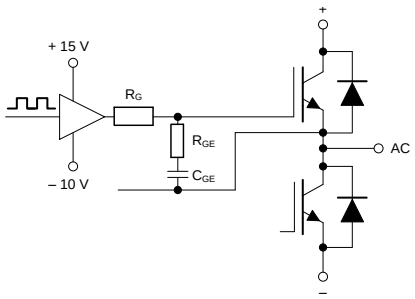


Figure 2. IGBTs with Gate Drive Circuitry for Gate Power Calculation

The total gate power dissipation is calculated by the following equation:

$$Pgate = Pdriver + (Q_{gate} \times f_{sw} \times \Delta Vgate) + (Cge \times f_{sw} \times \Delta Vgate^{2}) \quad (1)$$

where

- Q_{gate} = Total gate charge
- f_{sw} = Switching frequency
- ΔVgate = Gate driver output voltage swing

Consider the following example:

- An IGBT module with 1200 V and 200 A capacity (appropriate for <100 kW drives) having Q_{gate} = 1.65 µC.
- A switching frequency of 16 kHz, which is on the higher side for typical high power drives.
- A gate voltage, swinging from –15 V to 15 V. These values are a worst case condition, since IGBTs are typically driven with 15 V and either –5 V or –8 V.
- Gate-to-Emitter capacitance (Cge) = 20 nF (a typical value ranges between 1 nF and 20 nF).
- Gate-driver total power consumption (Pdriver) = approximately 600 mW. This value is estimated using the typical data sheet for an isolated IGBT gate-driver.

Using the values above:

$$Pgate = 0.6W + 0.792W + 0.288W = 1.68W \quad (2)$$

With de-rating, Equation 2 comes to 2W/IGBT.

The current output of a gate driver may or may not be sufficient to drive the IGBT, so designers use transistors for current boosting. This reference design is designed for 16 V on positive output and –8 V on the negative output, which takes care of the approximately 1 V drop in the transistors.

2 Design Features

The primary objective of this design is to replace the discrete components used in a power supply design with that of a PWM-controller-based, gate-drive power supply. Replacing these components leads to a reduced bill of materials (BOM) and increased reliability and performance.

2.1 Design Requirements

The system-level requirements for this design include:

- A PWM controller and a topology that helps scale the output power, while also driving high-power IGBTs.
- Isolated positive and negative rails should be 16 V and –8 V to power the isolated gate driver, the gates of the IGBTs, and the power-related sense circuitry (for isolated, current-measurement circuits).
- Continuous output power of 2 W to drive each IGBT.
- Support up to 6-A peak current, with an output voltage ripple of less than 200 mV.
- Ability to shut down the power supply to support Safe Torque Off (STO) feature to comply with standard IEC61800-5-1 and achieve other safety related compliances.

2.2 Topology Selection:

This reference design is intended to operate with a pre-regulated 24-V input. The open-loop, free-running oscillator of the PWM controller can be used, since it is a tightly regulated (within 5%) input source. The push-pull topology is basically a forward converter with two primary windings, which are used to create a dual-drive winding. This push-pull topology allows for more efficient use of the transformer core than the flyback or forward converters.

The advantage of push-pull converters over flyback and forward converters is that push-pull converters can be scaled up to higher powers. Further, both of the MOSFETs are connected to the low-side (unlike a half-bridge converter, which has one MOSFET connected to the high-side). The push-pull topology does not require gate drivers for the MOSFETs. Another advantage of using push-pull topology is that multiple transformers can be connected in parallel to generate the voltage rails required to power other IGBTs in the inverter. To translate the above requirements to the sub-system level, the requirements of the PWM controller, MOSFETs, transformer, and LDOs are listed as follows:

PWM Controller

- Should support push-pull topology
- Current control mode
- Shutdown feature to incorporate STO functionality (IEC61800-5-1 compliant)
- Operate from 24-V supply
- Defined dead time to avoid cross conduction

Power MOSFETs

- Should have a rated VDS ≥ 100 V to support a 24-V input supply
- Should support 1 A (min) drain current

Transformer Specifications (as per IEC61800-5-1)

- Two isolated outputs with V_{out1} = 8.7 V at 250 mA and V_{out2} = 8.7 V at 250 mA
- Switching frequency = 100 kHz
- Primary to secondary isolation = 7.4 kV for 1.2/50 us impulse voltage
- Type test voltage:
  - Primary to Secondary = 3.6 kVrms
  - Secondary1 to Secondary2 = 1.8 kVrms
- Spacings:
  - Primary to Secondary clearance = 8 mm
  - Secondary1 to Secondary2 clearance = 5.5 mm
  - Creepage distance = 9.2 mm
- Functional Isolation Primary and secondaries : 1.5k-V DC
- DC Isolation between secondaries: 1.5-kV DC

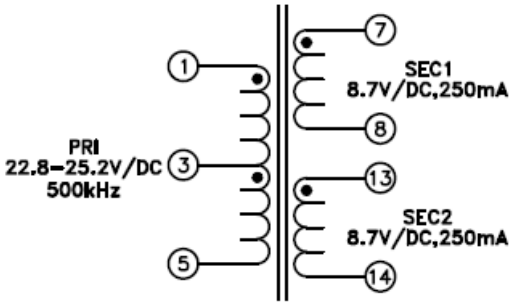


Figure 3. Push-Pull Transformer Symbol

Positive output LDO

- Adjustable output voltage
- Supports continuous output current up to 100 mA

Negative output LDO

- Adjustable output voltage
- Supports continuous output current up to 100 mA

3 Block Diagram

This reference design is intended for motor control, industrial inverters and many other applications where IGBT drivers are used and should help to significantly reduce design time while meeting all of the design requirements. The design files include schematics, bill of materials (BOM), layer plots, Altium files, Gerber files, and test results.

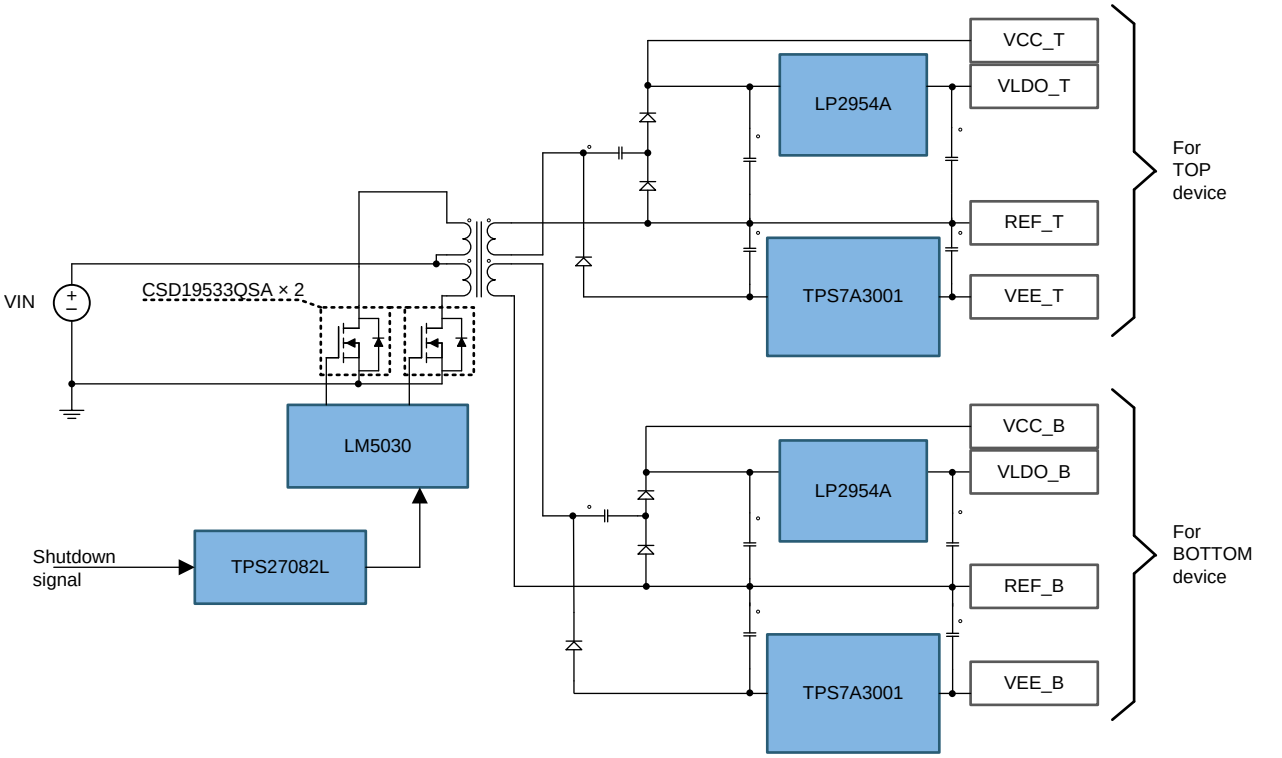


Figure 4. System Block Diagram

4 Highlighted Products

This reference design features the following devices, which were selected based on their specifications:

- *LM5030* PWM controller
- *CSD19533* NexFET™ power MOSFET
- *TPS27082* high-side load switch
- *LP2954A* micro power voltage regulator
- *TPS7A3001* linear regulator

For more information on each of these devices, see the respective product folders at www.ti.com or click on the links for the product folders on the first page of this reference design.

4.1 Component Selection

4.1.1 LM5030

The LM5030 high-voltage PWM controller contains all of the features needed to implement the push-pull topology, using current-mode control in a small 10-pin package. This device provides two alternating gate driver outputs. The LM5030 PWM controller includes a high-voltage, start-up regulator that operates over a wide input range of 14 V to 100 V.

Features include:

- Error amplifier
- Precision reference
- Dual mode current limit
- Slope compensation
- Soft start
- Sync capability
- Thermal shutdown

This high speed IC has a defined dead time of 135 ns and a 1 MHz-capable, single-resistor-adjustable oscillator.

4.1.2 CSD19533

This 100 V, 7.8 mΩ, SON 5 mm x 6 mm NexFET™ power MOSFET is designed to minimize losses in power-conversion applications. The maximum drain current capability is much higher than the 1A design requirement.

4.1.3 TPS27082L

The TPS27082L is a high side load switch that integrates a Power PFET and a control circuit in a tiny TSOT-23 package. The ON/OFF logic interface features hysteresis, which provides a robust logic interface even under very noisy operating conditions. The ON/OFF interface supports direct interfacing to low voltage GPIOs down to 1 V. The TPS27082L level shifts the ON/OFF logic signal to V_{IN} levels without requiring an external level shifter.

4.1.4 LP2954A

The LP2954A is a micropower voltage regulator with very low quiescent current (90 µA typical at 1 mA load) and very low dropout voltage (typically 60 mV at light loads and 470 mV at 250 mA load current). The adjustable LP2954A is provided in an 8-lead surface mount, small outline package. The adjustable version also provides a resistor network which can be pin strapped to set the output to 5 V. The tight line and load regulation (0.04% typical), as well as very low output temperature coefficient, make the LP2954A well suited for use as a low-power voltage reference.

4.1.5 TPS7A3001

The TPS7A3001, is a negative, high-voltage (–36 V), ultralow-noise (15.1 μVRMS, 72 dB PSRR) linear regulator capable of sourcing a maximum load of 200 mA. This linear regulator includes a CMOS logic-level-compatible enable pin and capacitor-programmable soft-start function that allows for customized power–management schemes.

4.2 Circuit Design

4.2.1 Input Section and Turn-On Mechanism:

In Figure 5, the input is pre-regulated 24-V (with ±5% accuracy) input applied to CONN1. Diode D1 is used for reverse input polarity protection. An optional LC filter (L1 and C1) may also be used for filtering out any noise in the input voltage coming from the back-panel in the field.

The LM5030 contains an internal high-voltage startup regulator. The input pin (V_{IN}) can be connected directly to line voltages as high as 100 V. Upon power up, the regulator is enabled and sources current into an external capacitor connected to the V_{CC} pin.

In this reference design, one 12-V zener diode is used to power the V_{CC} pin. This will keep the V_{CC} voltage greater than 8 V, effectively shutting off the internal startup regulator and saving power, and also reducing the controller dissipation.

The LM5030 Data Sheet, *LM5030 100 V Push-Pull Current Mode PWM Controller* (SNVS215), recommends a capacitor for the V_{CC} regulator between 0.1 μF to 50 μF. When the voltage on the V_{CC} pin reaches the regulation point of 7.7 V, the controller outputs are enabled. The outputs will remain enabled unless, V_{CC} falls below 6.1 V, the SS/SHUTDOWN pin is pulled to ground, or an over-temperature condition occurs. MOSFET Q1 A is also provided as a possible turn-on option but is not populated on the board.

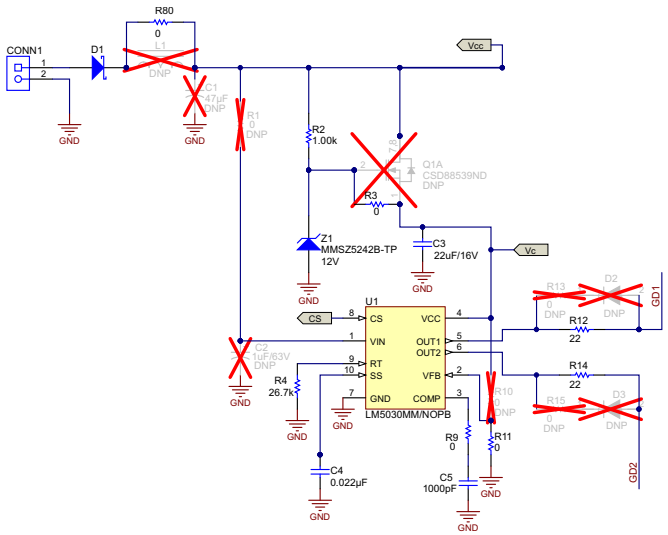


Figure 5. Input Section and Turn-On Mechanism

4.2.2 Oscillator Frequency Setting

Each output switches at half the oscillator frequency in a push-pull configuration. Assuming f_{sw} = 100 kHz: fosc = 2 * f_{sw} = 2*100 kHz = 200 kHz.

The LM5030 oscillator is set by a single external resistor, which is connected between the RT pin and the return. To set a desired oscillator frequency, the RT resistor can be calculated as:

$$RT = \frac{(1/f) - 172 \times 10^{-9}}{182 \times 10^{-12}} \quad (3)$$

where

- f = 200 kHz
- RT = 26.5 kΩ

The resistor value can also be approximated using the following graph, which is taken from the LM5030 Data Sheet, *LM5030 100 V Push-Pull Current Mode PWM Controller* (SNVS215).

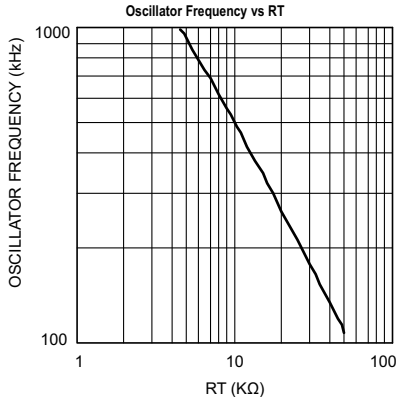


Figure 6. Oscillator Frequency vs. Timing Resistor RT

4.2.3 Soft-Start and Compensation

The soft-start feature allows the converter to gradually reach the initial, steady-state operating point, which reduces start-up stresses and surges. An internal, 10-uA current source and an external capacitor generate a ramping voltage signal that limits the error amplifier output during start-up. A reasonable time for a soft-start is 3 to 5 ms.

Using the standard formula for current in a capacitor (Equation 4):

$$I = C \times \frac{dV}{dt} \quad (4)$$

Using Equation 4, and assuming I = 10 uA, t = 3 ms, and dV = 1.4 V, the result is Css = 0.022 µF.

Figure 16 (in Section 5) shows the start-up time for the LM5030.

LM5030 can be run in open-loop operation by connecting the FB pin directly to ground. For open-loop design, the COMP pin can be connected to ground through a 1000-pF capacitor.

4.2.4 Power MOSFETs and Transformer

The power MOSFETs (CSD19533Q5A) are chosen because they have a drain-to-source voltage rating of 100 V and a drain current rating of at least 1 A. The source terminals of both MOSFETs are connected to a current-sense resistor for peak-current limiting and then given to the LM5030. There is a provision for a snubber circuit to be connected across the MOSFET, to avoid any ringing while switching the MOSFETs.

At the output of the transformers, two windings are provided for the two isolated outputs: VCC_T, VEE_T (for powering the TOP IGBTs) and VCC_B, VEE_B (for powering the BOTTOM IGBTs). The transformer is designed so that both secondaries provide 8.7 V (a 8-V output with a diode drop of 0.7 V).

While the negative output voltages (VEE_T and VEE_B) are generated directly, to generate the positive output voltages (VCC_T and VEE_B), the design uses cascaded voltage doublers (also called Greinacher voltage doublers). These doubler circuits generate 16 V at the VCC terminals.

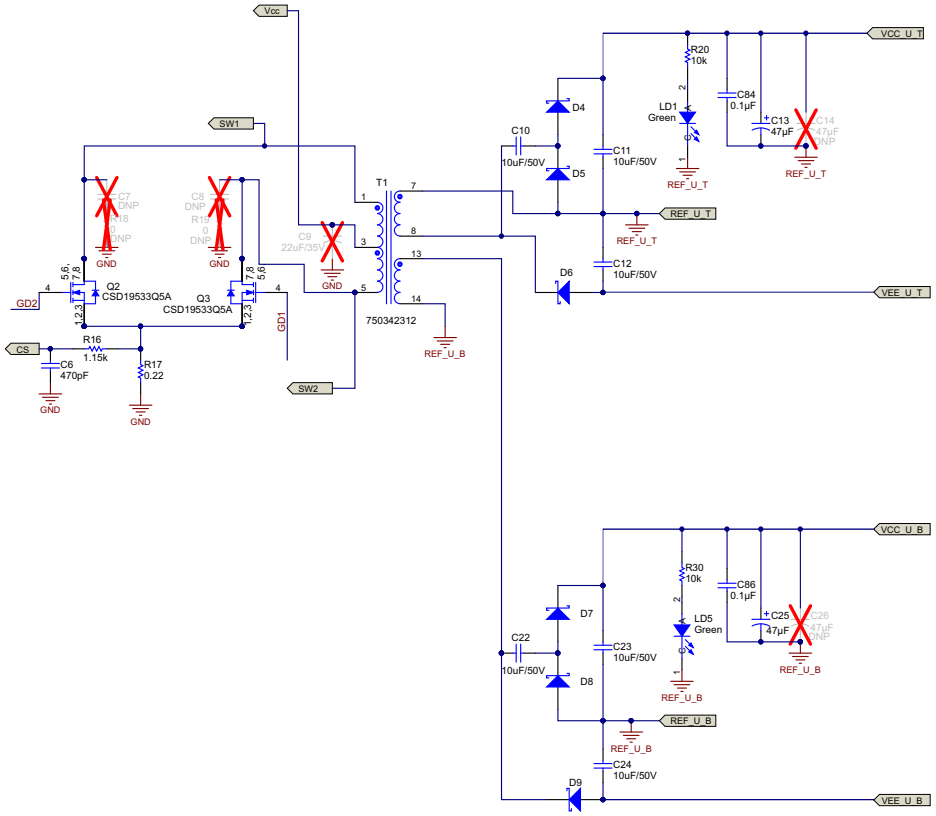


Figure 7. MOSFETs and Transformer

Turning an IGBT on and off amounts to charging and discharging large capacitive loads, so the peak charge current needs to be within the capability of the drive circuit. At the same time, the driver will have to draw this peak charge current from its power supply in a short period of time, so it is important to use proper by-pass capacitors for the power supply.

To achieve the minimum output ripple with high-current load transients, we use a 47-µF capacitor (with one more 47-µF capacitor in parallel, which is not populated) at each output.

4.2.5 Shutdown Operation of PWM Controller

This design provides the option to shut down the power supply to support a Safe Torque Off (STO) feature. The STO function is the most common and basic drive-integrated safety function. The STO features ensures that no torque-generating energy can continue to act upon a motor and prevents unintentional starting.

The SS-pin of the LM5030 can be used to disable the controller. If the SS-pin voltage is pulled down below 0.45 V (nominal), the controller will disable the outputs and enter a low-power state. The TPS27092L is a switch that integrates a power PFET and a control circuit. The on/off logic interface of this device features hysteresis, which provides a robust logic interface even under very noisy operating conditions. The on/off interface supports direct interfacing to low-voltage GPIOs down to 1 V because it level shifts the on/off logic signal to V_{IN} levels without requiring an external level shifter.

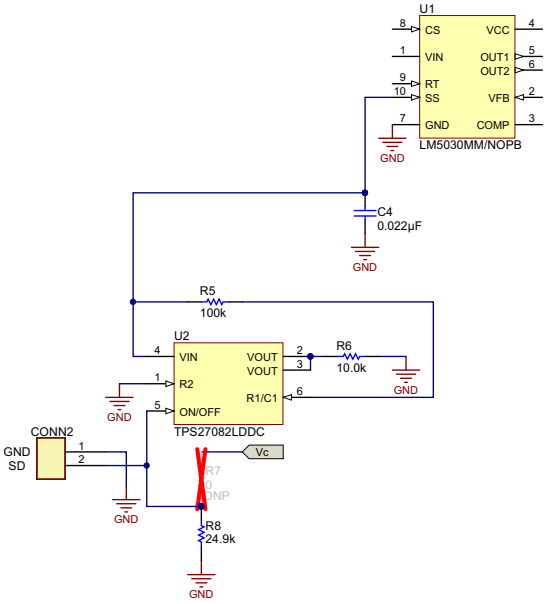


Figure 8. STO Feature Using the TPS27082L

4.2.6 Positive and Negative Output Regulators

4.2.6.1 Positive Regulator (LP2954A)

From the voltage doubler, the LP2954A is used as a post-regulator. The regulator can be programmed for any voltage between the 1.23 V reference and the 30 V maximum rating by using an external pair of resistors.

The complete equation for the output voltage is:

$$V_{OUT} = V_{REF} \times \left(1 + \frac{R1}{R2}\right) + (I_{FB} \times R1) \quad (5)$$

where

- V_{REF} = 1.23 V reference
- I_{FB} = Feedback pin bias current (–20 nA typ.)

The regulator can also be pin-strapped for 5-V operation, using the regulator's internal resistive divider by tying the OUT and SNS pins together, and then also tying the FB and 5-V TAP pins together. There is an option in the design to generate a 5-V output by populating the 0Ω-resistors (R21 and R22 in Figure 9). This 5-V output voltage is also provided at the output connector (VLDO_T and VLDO_B) for each phase.

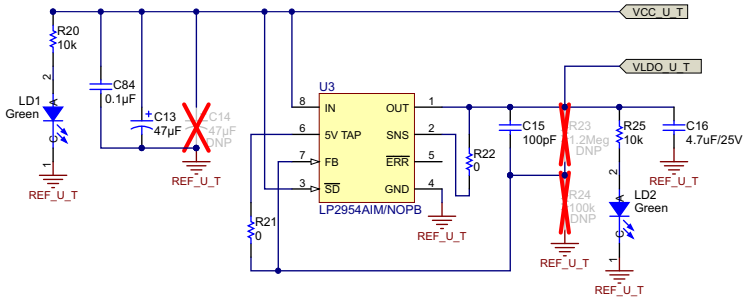


Figure 9. Positive Regulator (Set at 5 V)

As of now, the output of each LP2954A regulator is set to 5 V and the presence of VCC as well as the VLDO outputs is indicated, using the respective green LEDs. For 16 to 5 V conversion, it is important to calculate the power dissipation and check whether the LP2954A resistor is suitable for the conversion.

Equation 6 shows the power calculations for the LP2954A resistor:

$$PD(max) = (V_{in} - V_{out}) * I_{out} = 12.4\,V * 25\,mA = 310\,mW \quad (6)$$

where

- V_{in} = 17.4 V (worst case)
- V_{out} = 5 V
- I_{out} = 25 mA (max)
- and assuming TA = 60ºC

Referring to the LP2954A Data Sheet, *LP2954/LP2954A 5 V and Adjustable Micropower Low-Dropout Voltage Regulators* (SNVS096), $T_{j(max)}$ = 125ºC, and a derating of 10ºC gives $T_{j(max)}$ = 115ºC

$$\theta_{JA} \leq [\,(Tj(max)\text{-}TA)/PD(max)\,]$$
$$\leq [(115\text{-}60)/0.31]$$
$$\leq 177.4°C/W \quad (7)$$

Referring to the LP2954A Data Sheet, *LP2954/LP2954A 5 V and Adjustable Micropower Low-Dropout Voltage Regulators*, page 2, (SNVS096), it is clear that LP2954A can handle the power for this condition, as the LP2954A Data Sheet lists θ_{JA} = 160°C/W.

4.2.6.2 Negative Regulator (TPS7A3001)

The output coming from the transformer after diode rectification is given to the TPS7A3001, the negative regulator. The TPS7A3001 has an output voltage range of –1.174 V to –33 V. The nominal output voltage of the regulator is set by two external resistors. To ensure stability under no-load conditions, this resistive network must provide a current equal to or greater than 5 µA.

R1 and R2 can be calculated for any output voltage, using Equation 8:

$$R1 = R2\left(\frac{V_{OUT}}{V_{REF}} - 1\right)$$

where

- $\frac{V_{OUT}}{R_1 + R_2} \geq 5\mu A$
- V_{REF} = –1.179 V reference (8)

Using Equation 8, and considering R2 = 102 kΩ to get the output voltage of –5 V, R1 is calculated as 330 kΩ.

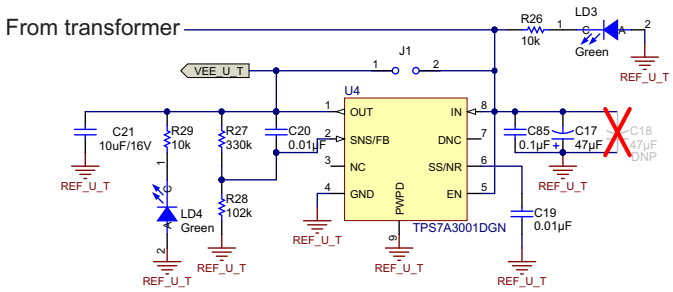


Figure 10. Negative Regulator (Set at –5 V)

As of now, the output of each TPS7A3001 resistor is set to -5 V and the presence of the VEE output is indicated by a green LED. If it is not necessary to use the negative regulator, and the output of the transformer is directly required, there is an option to bypass the regulator by using a jumper (J1 in Figure 10).

For –8.7 V to –5 V conversion, it is important to calculate the power dissipation and to check whether TPS7A3001 is able to do the conversion.

Equation 9 shows the power calculations for TPS7A3001:

$PD(max) = (V_{in} – V_{out}) \times I_{out} = 3.7\ V \times 25\ mA = 92.5\ mW$

where

- V_{in} = –8.7 V
- V_{out} = –5 V
- I_{out} = –25 mA (max)
- and assuming TA = 60°C (9)

Referring to the TPS7A3001 Data Sheet, *TPS7A3001 –36 V, –200 mA, Ultralow-Noise, Negative Linear Regulator*,(SBVS125), $T_{j(max)}$ = 125°C, and a derating of 10°C results in $T_{j(max)}$ = 115°C.

$\theta_{JA} \leq [\ (Tj(max) – TA) / PD(max)\ ]$

$\leq [\ (115 – 60) / 0.0925]$

$\leq 594.59°C/W$

Referring to the TPS7A3001 Data Sheet, *TPS7A3001 –36 V, –200 mA, Ultralow-Noise, Negative Linear Regulator*, (SBVS125), it is clear that the resistor can handle the required power for this condition, as the TPS7A3001 Data Sheet shows θ_{JA} = 55.09°C/W.

4.2.7 Three Transformers to Power All Three IGBT Arms of 3-phase Inverter

The push-pull topology allows connection of transformers in parallel, which allows the IGBTs in all three arms (U, V, and W) to be powered using a single controller..

The outputs are as shown in Table 1:

Table 1. Outputs for Top and Bottom IGBTs (1)

Phase	For TOP IGBT	For BOTTOM IGBT
U	VCC_U_T	VCC_U_B
	VEE_U_T	VEE_U_B
	VLDO_U_T	VLDO_U_B
	REF_U_T	REF_U_B
V	VCC_V_T	VCC_V_B
	VEE_V_T	VEE_V_B
	VLDO_V_T	VLDO_V_B
	REF_V_T	REF_V_B
W	VCC_W_T	VCC_W_B
	VEE_W_T	VEE_W_B
	VLDO_W_T	VLDO_W_B
	REF_W_T	REF_W_B

(1) This table shows outputs for all three arms.

4.2.8 Scalability Option for Higher-Power Industrial Drives:

This design is intended to be used with IGBT modules with ratings of 1200 V/200 A. If higher power IGBT modules are to be powered, the same reference design can be scaled up to for higher power by changing the transformer design. The existing transformers have secondary, output current ratings of 250 mA each. This rating can be increased to meet the requirement for higher-power Industrial drives.

5 Test Data

5.1 Section 1: Functional Test Results for the LM5030

Figure 11, Figure 12, and Figure 13 show the MOSFET gate drive signals and the dead-time between the two output pins of the LM5030. It can be seen from Figure 12 and Figure 13 that the dead-time between the two gate drive signals is 130.8 ns and 134 ns respectively. The typical value of dead time from the LM5030 datasheet is 135 ns.

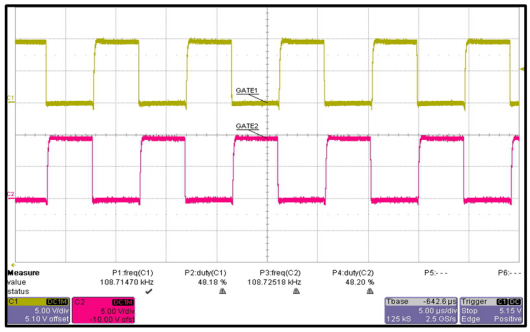


Figure 11. Gate Drive Signals for Both MOSFETs (Q2 and Q3 in Figure 7)

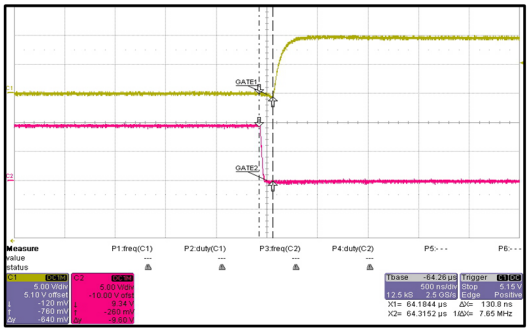


Figure 12. Dead-Time Between Gate-Drive Signals (Rising Edge of GATE1 Shown)

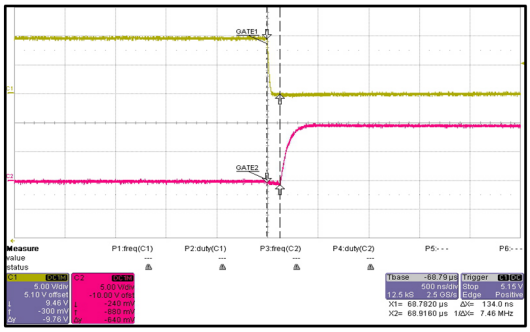


Figure 13. Dead-Time Between Gate-Drive Signals (Falling Edge of GATE1 Shown)

Figure 14 and Figure 15 show the MOSFET gate versus the MOSFET drain signals for Q2 and Q3 (in Figure 7). The duty cycle is currently set to the maximum (by connecting the COMP pin to ground through a 1000-pF capacitor shown in Section 4.2.1)

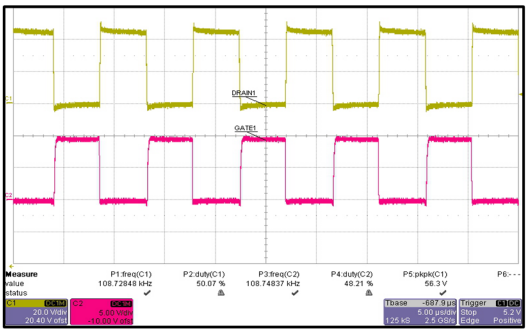


Figure 14. Gate Drive versus Drain Voltage for Q2

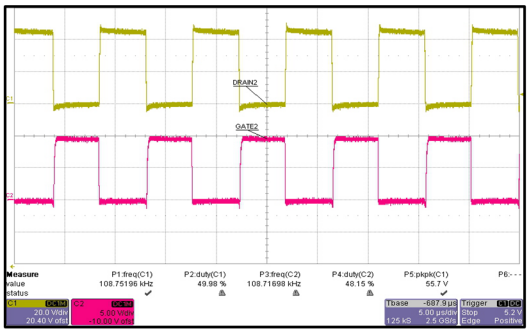


Figure 15. Gate Drive versus Drain Voltage for Q3

Figure 16 shows the soft-start operation of the PWM controller LM5030. As per the calculations, the SS time is set to 3 ms and the test waveform also shows the same start-up time for LM5030.

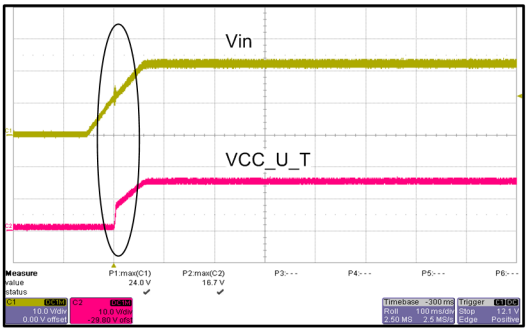


Figure 16. Soft-Start for LM5030

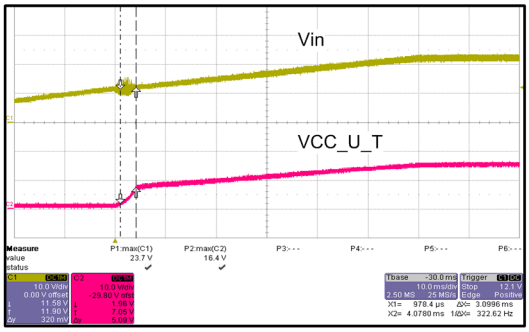


Figure 17. Zoomed Waveform Showing t_{ss} = 3 ms

TPS27082L is used as a switch to facilitate the STO feature for the industrial drives. The LM5030 SS-pin has dual functions. The LM5030-SS pin is used for soft-start operation and also for shutdown during STO. The soft-start operation and shutdown has been tested, and the waveform in Figure 18 shows the shutdown signal along with the outputs going to zero.

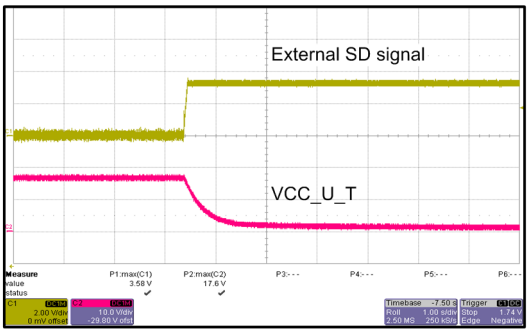


Figure 18. Shutting Down the LM5030 Using an External Signal

LM5030 is a current mode-control device. It contains two levels of overcurrent protection. Therefore, if the voltage on the current-sense comparator exceeds 0.5 V, the present cycle is terminated (cycle-by-cycle current limit). If the voltage on the current sense comparator exceeds 0.625 V, the controller will terminate the present cycle and discharge the soft-start capacitor.

The LM5030 CS and PWM comparators are fast, so they will respond to short-duration noise pulses. The second level threshold is intended to protect the power converter by initiating a low-duty, cycle hiccup mode when any abnormally high, fast-rising currents occur. During excessive loading, the first-level threshold will always be reached. The output characteristic of the converter will be that of current source. However, this sustained current level can cause excessive temperatures in the power train, especially in the output rectifiers.

If the second-level threshold is reached, the soft-start capacitor will be fully discharged. A retry will commence following discharge detection. The second-level threshold will only be reached when a high dV/dt is present at the current-sense pin. The signal must be fast enough to reach the second-level threshold before the first-threshold detector turns off the driver. This can usually happen for a saturated power inductor, or for a shorted load. Excessive filtering on the CS pin, an extremely low-value, current-sense resistor, or an inductor that does not saturate with excessive loading may prevent the second-level threshold from ever being reached.

Figure 19 shows the voltage waveform on the Current-Sense (CS) pin of the LM5030, with all of the outputs loaded with a 2 W load.

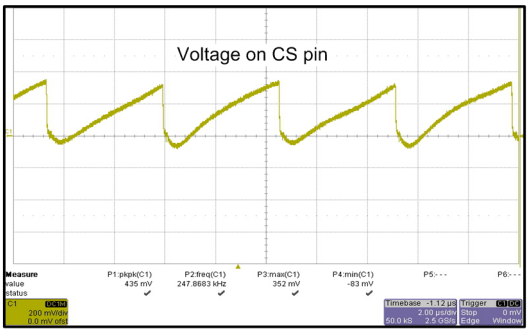


Figure 19. Voltage Waveform Captured on the CS Pin of the LM5030

Figure 20 and Figure 21 show the outputs of MOSFETs when the MOSFETs start to switch, and before the MOSFETs go to the doubler for further rectification (on both positive and negative outputs).

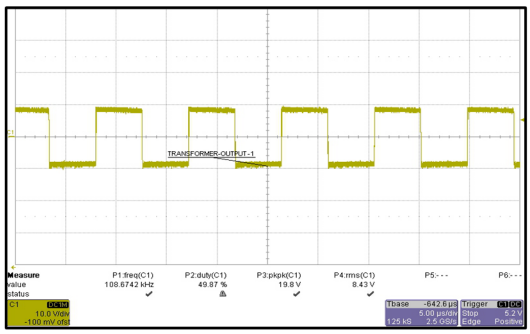


Figure 20. Transformer Secondary Output #1

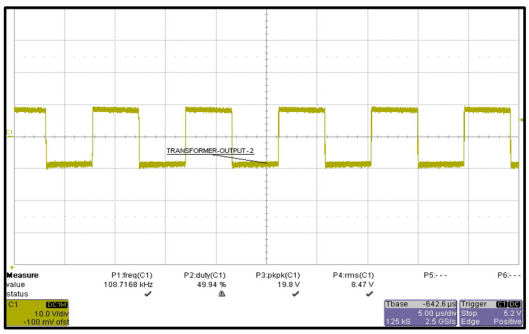


Figure 21. Transformer Secondary Output #2

5.2 Section 2: Output Ripple Under Different Test Conditions

With all of the outputs loaded with 2 W of output power, the ripple at the 16-V output and –8 V outputs are captured. On the 16-V output, the peak-to-peak ripple voltage is 59 mV and on the –8 V output, the peak-to-peak ripple voltage is 50 mV. Figure 22 and Figure 23 show the waveforms for the same.

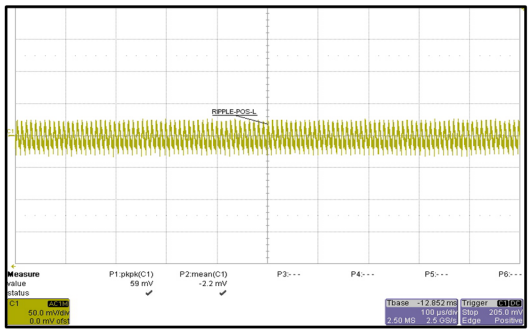


Figure 22. Ripple Voltage on 16 V Output

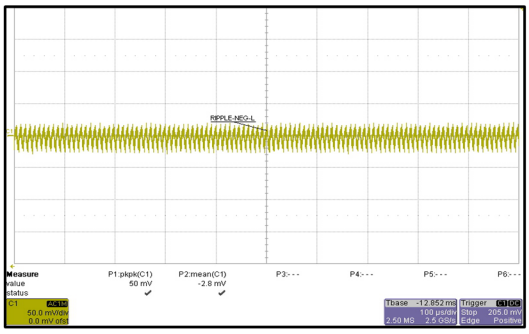


Figure 23. Ripple Voltage on –8 V Output

Both the linear regulators (LP2954A and TPS7A3001) are tested for ripple at the output with load of 25 mA on each. Figure 24 and Figure 25 show the ripple waveforms on the same.

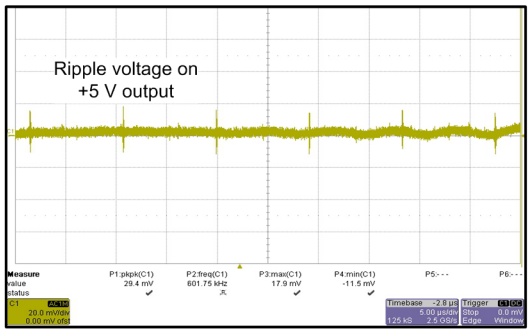


Figure 24. Ripple on 5 V Output (LP2954A)

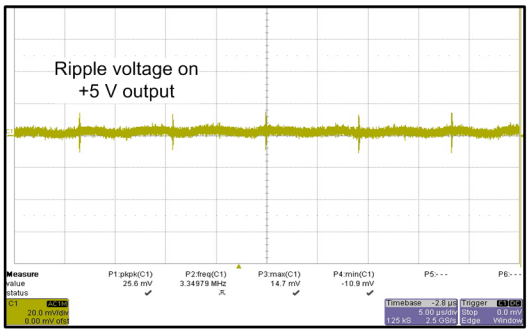


Figure 25. Ripple on –5 V Output (TPS7A3001)

5.3 Section 3: Regulation and Efficiency

The efficiency is measured with all six outputs loaded with equal loads. When all the outputs were loaded with 2 W load each, the efficiency is around 78% as shown in Figure 26.

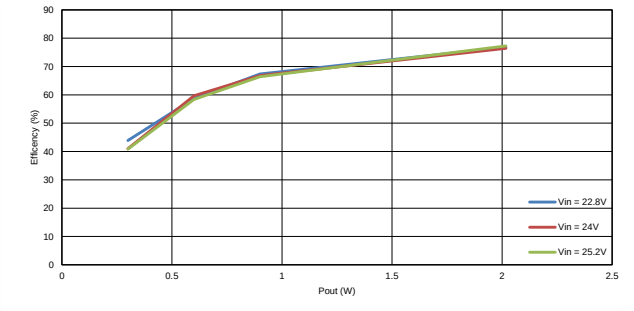


Figure 26. Efficiency at Different V_{in} Values

The regulation and cross-regulation data is captured at different V_{in} values as shown in Figure 27, Figure 28, and Figure 29. While measuring the regulation and cross-regulation, five (out of six) outputs are loaded with 2 W load each and one output is varied from 0% to 100%. The cross regulation is included so as to show that there is not much interference when TOP IGBT is powered and Bottom IGBT is not powered (or TOP IBGT is not powered and Bottom IGBT is powered).

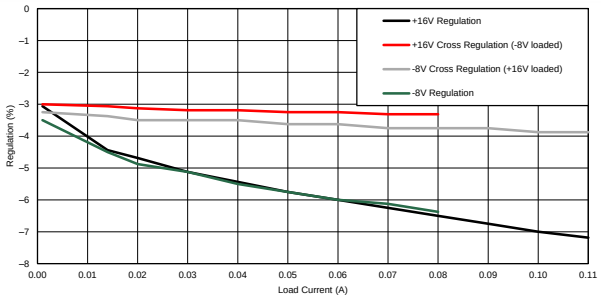


Figure 27. Regulation and Cross Regulation (V_{in} = 22.8 V)

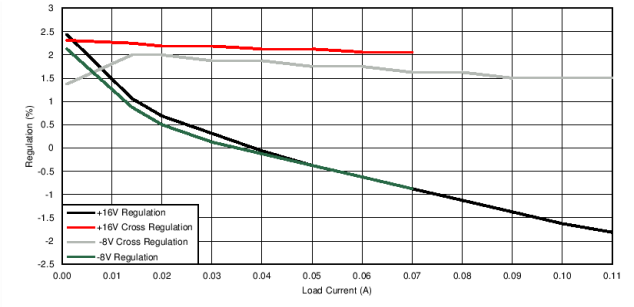


Figure 28. Regulation and Cross Regulation (V_{in} = 24 V)

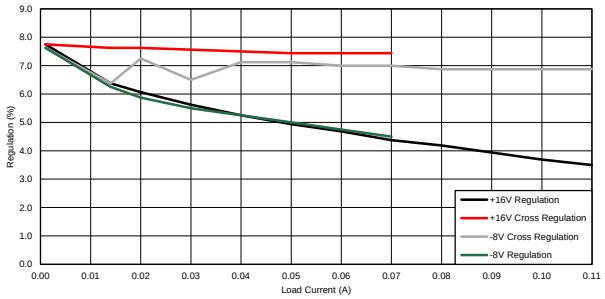


Figure 29. Regulation and Cross Regulation (V_{in} = 25.2 V)

5.4 Section 4: Isolation Test Results

The design is tested for and has successfully passed a 7 kV impulse test (for 1.2/50 us pulse). It has also passed a type-test isolation voltage tests as per the design specifications.

5.5 Section 5: Testing with ISO5500 and IGBTs

To duplicate the actual drive testing, this reference design is tested with TI ISO5500 EVMs along with 1200 V IGBTs. Two 16-kHz, complementary PWM signals for IGBT gate driving are generated using a Piccolo LaunchPAD™ from TI. They are fed to two ISO5500 (each connected to one 1200 V IGBT). The IGBTs are connected in half-bridge form, as shown in Figure 30 with 1-kΩ load connected at the output. The image of the set-up with all boards is also shown in Figure 31.

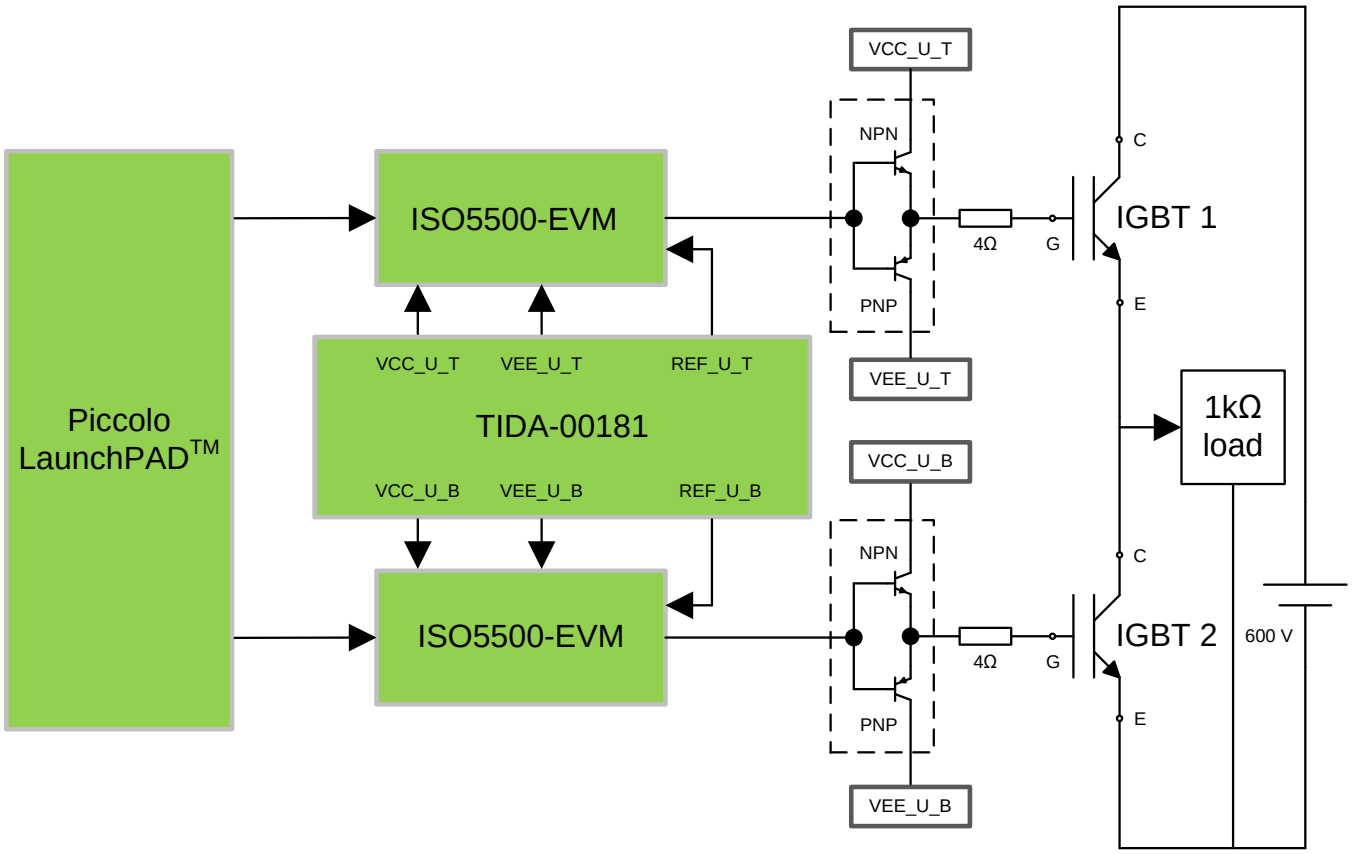


Figure 30. Set-Up for Testing TIDA-00181 design with ISO5500 and IGBTs

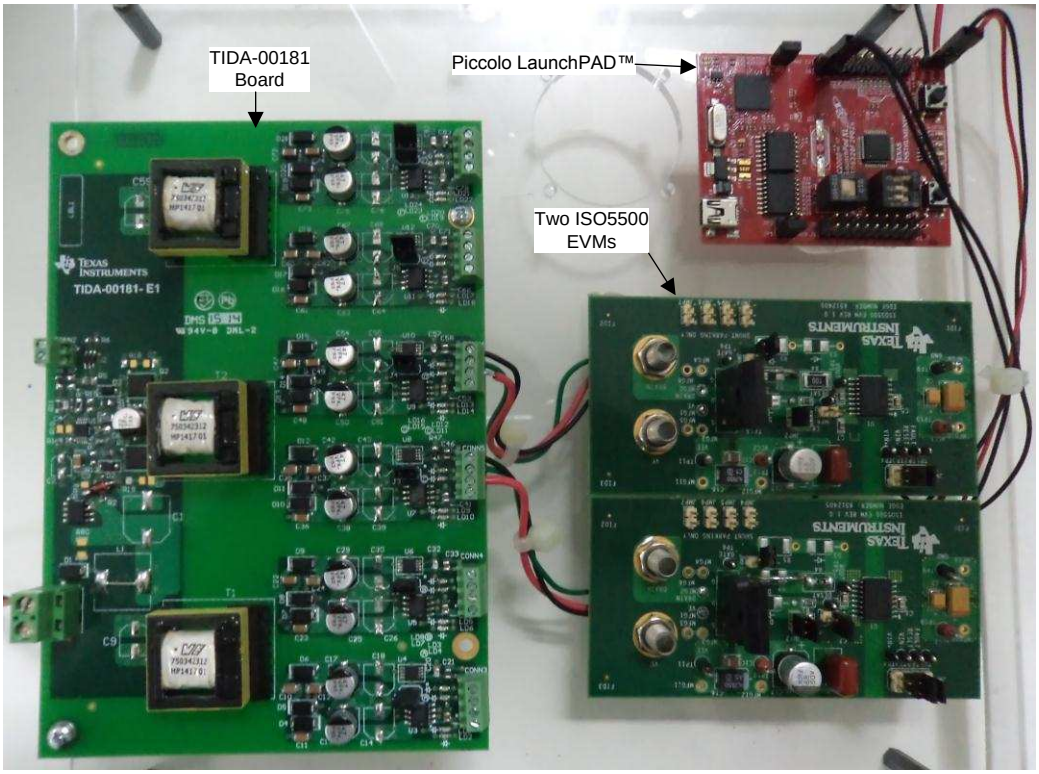


Figure 31. Set-Up

To measure the ripple, both ISO5500s are applied with the TIDA-00181 power supply and the IGBT arm is applied with a 600 V supply. Figure 32 and Figure 33 show the 200 mV ripple which meets the specification of the reference design.

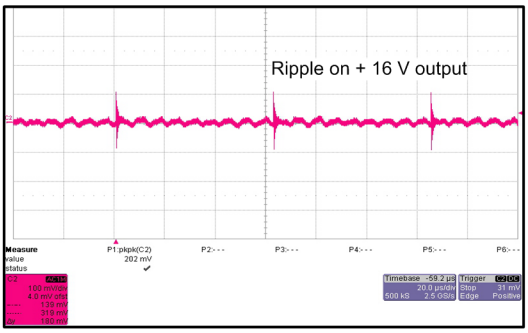


Figure 32. Ripple on 16 V output (For dv/dt = 11.9*E9 on the Output Load)

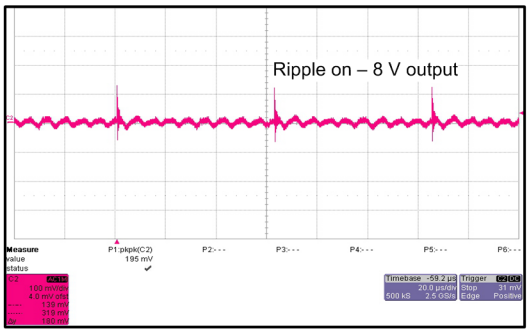


Figure 33. Ripple on –8 V Output (for dv/dt = 11.9*E9 on the Output Load)

The current boost transistors (NPN and PNP) are used to boost the output current of the ISO5500 in order to drive the IGBTs. With 6-A peak current while charging the internal capacitance of IGBTs, the ripple on the VCC and VEE outputs of power supply are also measured. Figure 34 and Figure 35 show the ripple voltage along with the IGBT gate capacitor charging current spikes.

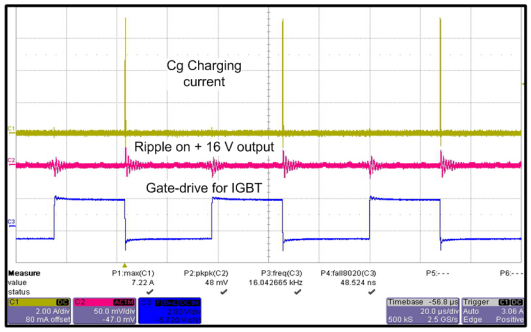


Figure 34. Ripple on 16-V output (for 6 A peak load current with IGBTs)

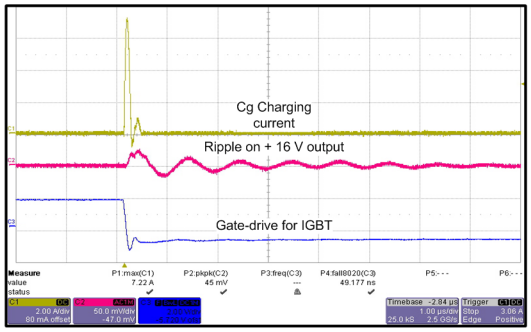


Figure 35. Zoomed Waveforms

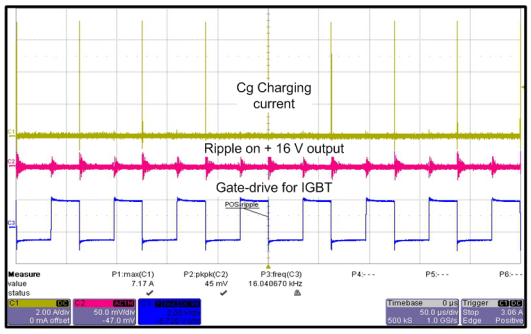


Figure 36. Ripple on –8 V output for 6-A peak load current with IGBTs

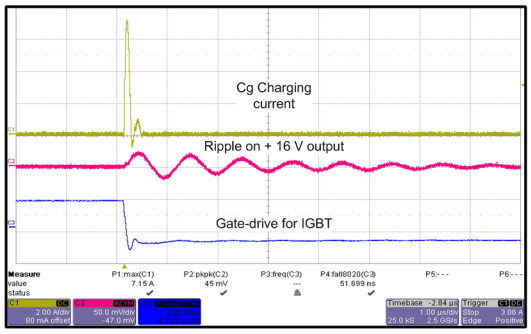


Figure 37. Zoomed Waveforms

6 Layout Guidelines for LM5030

The LM5030 contains two levels of over-current protection. If the voltage on the current sense comparator exceeds 0.5 Volts, the present cycle is terminated (cycle by cycle current limit). If the voltage on the current sense comparator exceeds 0.625 Volts, the controller will terminate the present cycle and discharge the soft-start capacitor.

A small RC filter, located near the controller, is recommended for the CS pin. An internal MOSFET discharges the current sense filter capacitor at the conclusion of every cycle, to improve dynamic performance. The LM5030 CS and PWM comparators are very fast, and therefore will respond to short duration noise pulses. Layout considerations are critical for the current sense filter and sense resistor. The capacitor associated with the CS filter must be placed very close to the device and connected directly to the pins of the IC (CS and RTN).

If a current sense resistor located in the drive transistor sources is used, for current sense, a low inductance resistor should be chosen. In this case, all of the noise sensitive low power grounds should be commoned together around the IC. Then a single connection should be made to the power ground (sense-resistor ground point). The RT resistor should also be located very close to the device and connected directly to the pins of the IC (RT and GND).

7 Design Files

7.1 Schematics

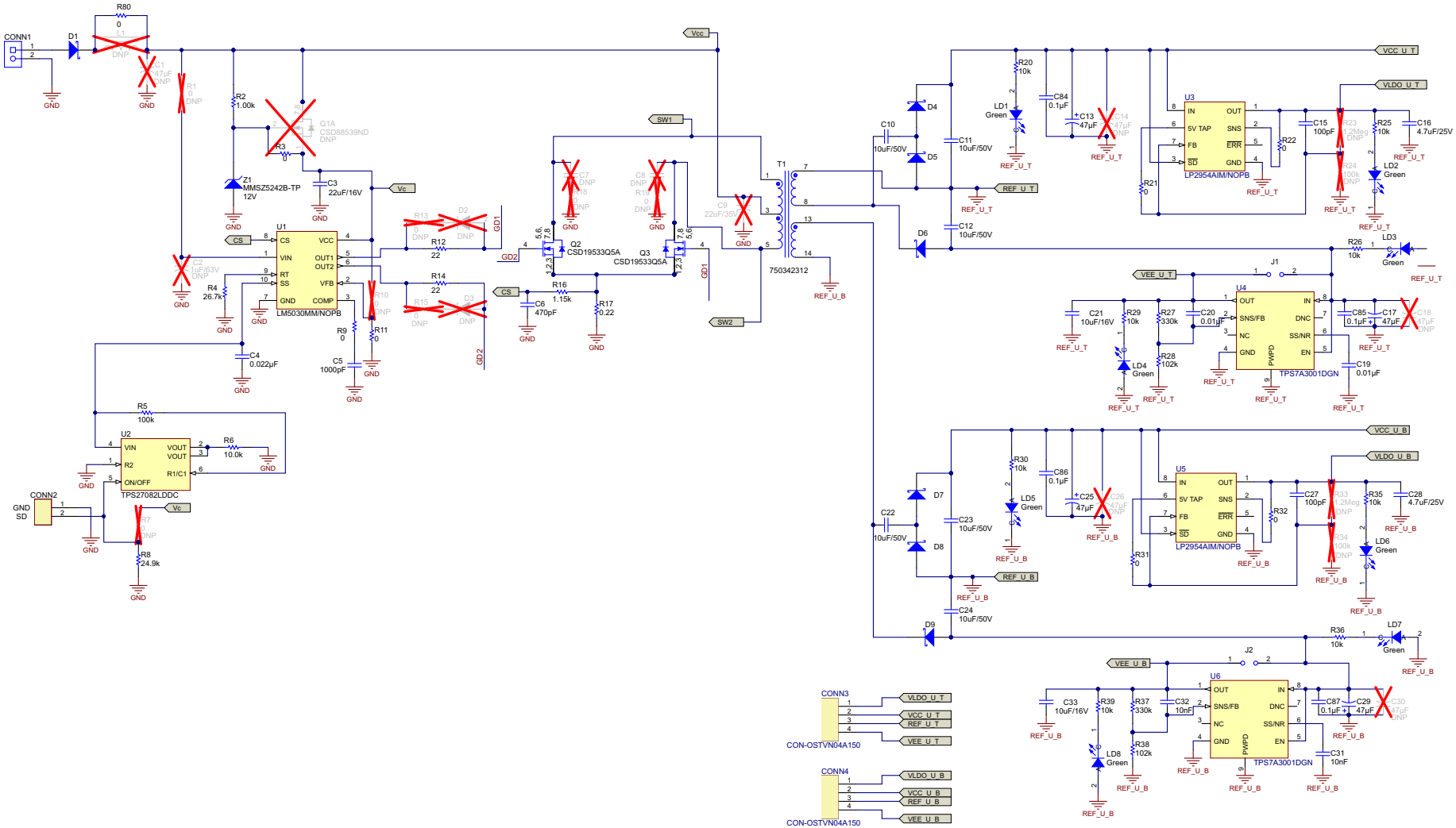


Figure 38. Schematics Page 1

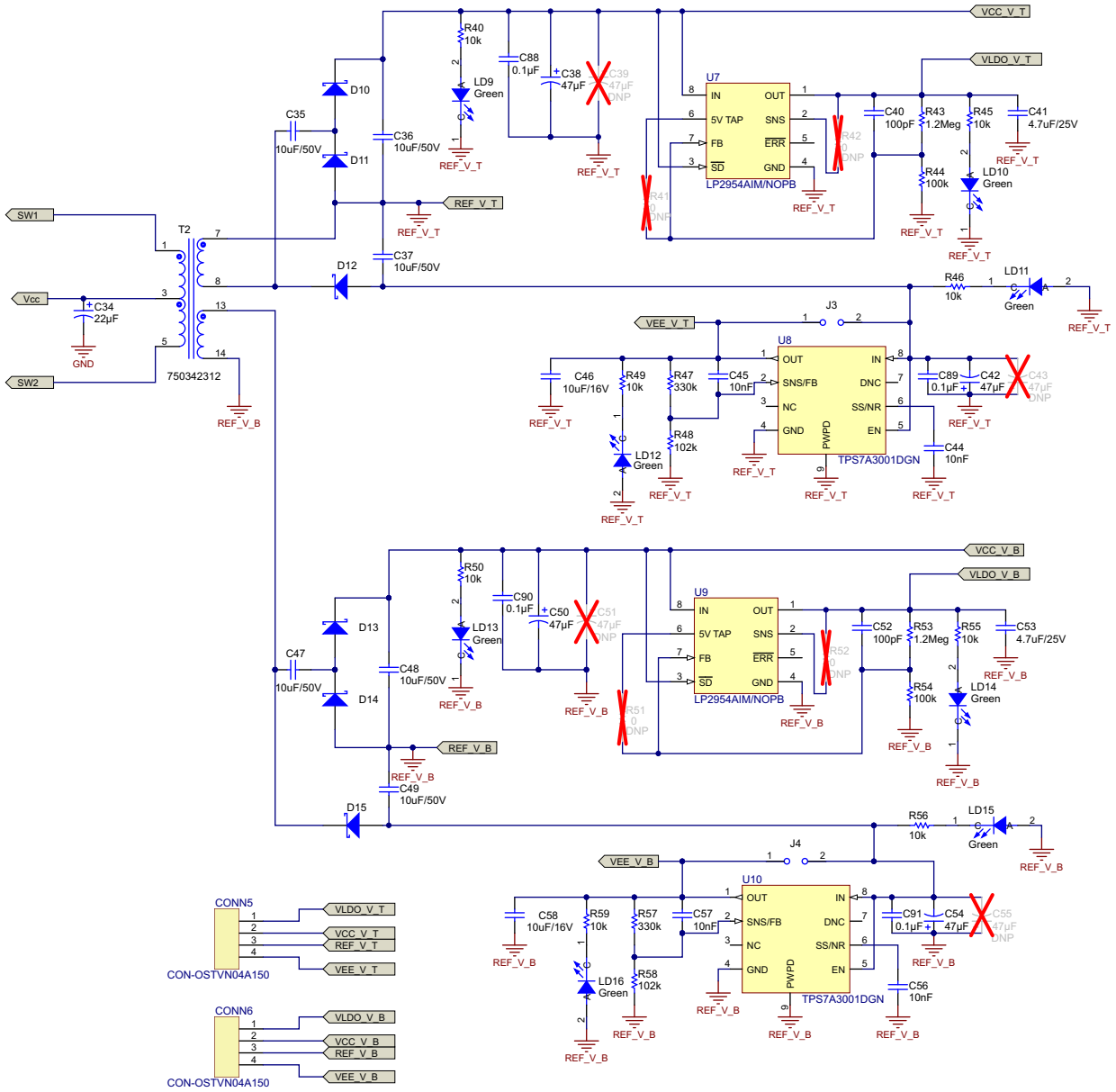


Figure 39. Schematics Page 2

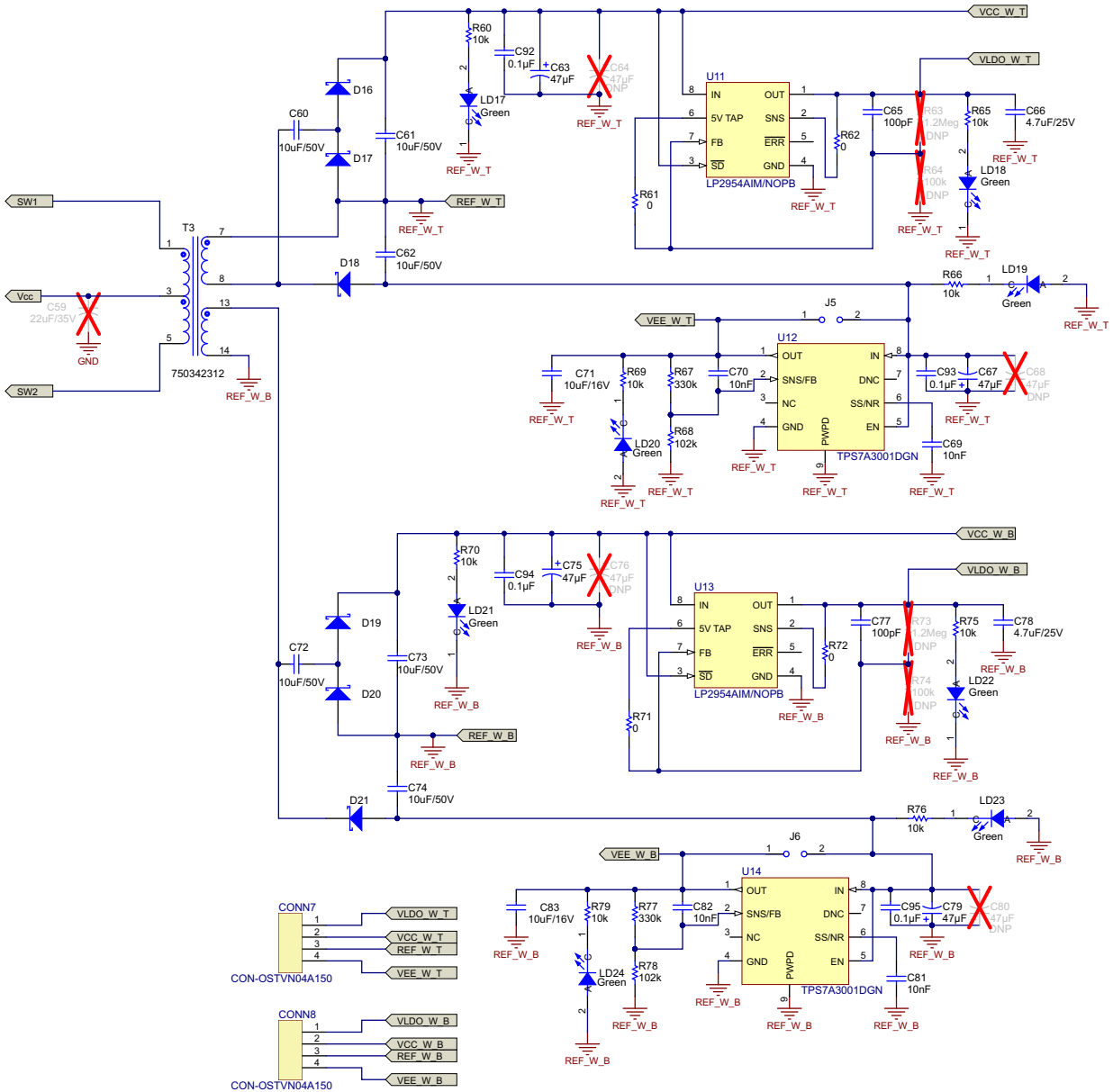


Figure 40. Schematics Page 3

7.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA00181. Table 2 shows the BoM for this reference design.

Table 2. BOM

SL. NO.	FITTED	QUANTITY	DESIGNATOR	DESCRIPTION	PARTNUMBER	MANUFACTURER	ROHS	PACKAGE REFERENCE
1	Fitted	1	!PCB	Printed Circuit Board	TIDA-00181	Any	O	
2	Not Fitted	0	C1	CAP, AL, 47uF, 80V, +/-20%, 0.7 ohm, SMD	EEE-FK1K470P	Panasonic	Y	SMT Radial G
3	Not Fitted	0	C2	CAP, AL, 1uF, 63V, +/-20%, ohm, SMD	EMVE630ADA1R0MD55G	Nippon Chemi-Con	Y	D55
4	Fitted	1	C3	CAP, CERM, 22uF, 16V, +/-20%, X5R, 1206	1206YD226MAT2A	AVX	Y	1206
5	Fitted	1	C4	CAP, CERM, 0.022uF, 25V, +/-5%, C0G/NP0, 0805	C2012C0G1E223J	TDK	Y	0805
6	Fitted	1	C5	CAP, CERM, 1000pF, 25V, +/-10%, X7R, 0805	GRM216R71E102KA01D	MuRata	Y	0805
7	Fitted	1	C6	CAP, CERM, 470pF, 50V, +/-10%, X7R, 0805	CC0805KRX7R9BB471	Yageo America	Y	0805
8	Not Fitted	0	C7, C8	CAP, CERM, 1000pF, 25V, +/-10%, X7R, 0805	GRM216R71E102KA01D	MuRata	Y	0805
9	Not Fitted	0	C9, C59	CAP, AL, 22uF, 35V, +/-20%, 1 ohm, SMD	EEE-FC1V220P	Panasonic	Y	SMT Radial D
10	Fitted	18	C10, C11, C12, C22, C23, C24, C35, C36, C37, C47, C48, C49, C60, C61, C62, C72, C73, C74	CAP, CERM, 10uF, 50V, +/-10%, X5R, 1206_190	CGA5L3X5R1H106K160AB	TDK	Y	1206_190
11	Fitted	12	C13, C17, C25, C29, C38, C42, C50, C54, C63, C67, C75, C79	CAP, AL, 47uF, 35V, +/-20%, 0.36 ohm, SMD	EEE-FK1V470P	Panasonic	Y	SMT Radial D
12	Not Fitted	0	C14, C18, C26, C30, C39, C43, C51, C55, C64, C68, C76, C80	CAP, AL, 47uF, 35V, +/-20%, 0.36 ohm, SMD	EEE-FK1V470P	Panasonic	Y	SMT Radial D
13	Fitted	6	C15, C27, C40, C52, C65, C77	CAP, CERM, 100pF, 50V, +/-10%, C0G/NP0, 0805	C0805C101K5GACTU	Kemet	Y	0805
14	Fitted	6	C16, C28, C41, C53, C66, C78	CAP, CERM, 4.7uF, 25V, +/-10%, X5R, 0805	C2012X5R1E475K125AB	TDK	Y	0805
15	Fitted	12	C19, C20, C31, C32, C44, C45, C56, C57, C69, C70, C81, C82	CAP, CERM, 0.01uF, 16V, +/-5%, C0G/NP0, 0805	B37947K9103J62	EPCOS Inc	Y	0805
16	Fitted	6	C21, C33, C46, C58, C71, C83	CAP, CERM, 10uF, 16V, +/-20%, X5R, 0805	0805YD106MAT2A	AVX	Y	0805
17	Fitted	1	C34	CAP, AL, 22uF, 35V, +/-20%, 1 ohm, SMD	EEE-FC1V220P	Panasonic	Y	SMT Radial D
18	Fitted	12	C84, C85, C86, C87, C88, C89, C90, C91, C92, C93, C94, C95	CAP, CERM, 0.1uF, 50V, +/-5%, X7R, 0805	08055C104JAT2A	AVX	Y	0805
19	Fitted	1	CONN1	Terminal Block, 2x1, 5.08mm, TH	282841-2	TE Connectivity	Y	10.16x15.2x9mm
20	Fitted	1	CONN2	Terminal Block, 4x1, 2.54mm, TH	OSTVN02A150	On Shore Technology Inc	Y	TERM_BLK, 2pos, 2.54mm
21	Fitted	6	CONN3, CONN4, CONN5, CONN6, CONN7, CONN8	CONN TERM BLOCK 2.54MM 4POS PCB	STVN04A150	On Shore Technology Inc	Y	TERM_BLK, 4pos, 2.54mm
22	Fitted	1	D1	Diode, Schottky, 60V, 2A, SMA	B260A-13-F	Diodes Inc.	Y	SMA
23	Not Fitted	0	D2, D3	Diode, Signal, 300-mA, 75-V, 350-mW	1N4148W-7-F	Diodes		SOD-123
24	Fitted	18	D4, D5, D6, D7, D8, D9, D10, D11, D12, D13, D14, D15, D16, D17, D18, D19, D20, D21	Diode, Schottky, 90V, 1A, SMA	B190-13-F	Diodes Inc.	Y	SMA
25	Not Fitted	0	FID1, FID2, FID3, FID4, FID5, FID6	Fiducial mark. There is nothing to buy or mount.	N/A	N/A		Fiducial
26	Fitted	4	H1, H2, H3, H4	Machine Screw, Round, #4-40 x 1/4, Nylon, Philips panhead	NY PMS 440 0025 PH	BandF Fastener Supply	Y	Screw
27	Fitted	4	H5, H6, H7, H8	Standoff, Hex, 0.5"L #4-40 Nylon	1902C	Keystone	Y	Standoff

Table 2. BOM (continued)

SL. NO.	FITTED	QUANTITY	DESIGNATOR	DESCRIPTION	PARTNUMBER	MANUFACTURER	ROHS	PACKAGE REFERENCE
28	Fitted	6	J1, J2, J3, J4, J5, J6	Header, Male 2-pin, 100mil spacing,	PEC02SAAN	Sullins		0.100 inch x 2
29	Not Fitted	0	L1	Inductor, Shielded, Ferrite, 2.2mH, 0.65A, 1.94 ohm, SMD	MSS1210-225KE	Coilcraft	Y	Inductor, 12.3x10x12.3mm
30	Fitted	1	LBL1	Thermal Transfer Printable Labels, 0.650" W x 0.200" H - 10,000 per roll	THT-14-423-10	Brady	Y	PCB Label 0.650"H x 0.200"W
31	Fitted	24	LD1, LD2, LD3, LD4, LD5, LD6, LD7, LD8, LD9, LD10, LD11, LD12, LD13, LD14, LD15, LD16, LD17, LD18, LD19, LD20, LD21, LD22, LD23, LD24	LED SmartLED Green 570NM	LG L29K-G2J1-24-Z	OSRAM		0603
32	Not Fitted	0	Q1	MOSFET, N-CH, 60V, 6.3A, SO-8	CSD88539ND	Texas Instruments	Y	SO-8
33	Fitted	2	Q2, Q3	MOSFET, N-CH, 100V, 13A, SON 5x6mm	CSD19533Q5A	Texas Instruments	Y	SON 5x6mm
34	Not Fitted	0	R1, R7, R10, R13, R15, R18, R19, R41, R42, R51, R52	RES, 0 ohm, 5%, 0.125W, 0805	CRCW08050000Z0EA	Vishay-Dale	Y	0805
35	Fitted	1	R2	RES, 1.00k ohm, 1%, 0.125W, 0805	CRCW08051K00FKEA	Vishay-Dale	Y	0805
36	Fitted	11	R3, R9, R11, R21, R22, R31, R32, R61, R62, R71, R72	RES, 0 ohm, 5%, 0.125W, 0805	CRCW08050000Z0EA	Vishay-Dale	Y	0805
37	Fitted	1	R4	RES 26.7K OHM 1/8W 1% 0805 SMD	RC0805FR-0726K7L	Yageo	Y	0805
38	Fitted	3	R5, R44, R54	RES, 100k ohm, 1%, 0.125W, 0805	ERJ-6ENF1003V	Panasonic	Y	0805
39	Fitted	1	R6	RES, 10.0k ohm, 1%, 0.125W, 0805	CRCW080510K0FKEA	Vishay-Dale	Y	0805
40	Fitted	1	R8	RES, 24.9k ohm, 1%, 0.125W, 0805	ERJ-6ENF2492V	Panasonic	Y	0805
41	Fitted	2	R12, R14	RES, 22 ohm, 5%, 0.125W, 0805	CRCW080522R0JNEA	Vishay-Dale	Y	0805
42	Fitted	1	R16	RES, 1.15k ohm, 1%, 0.125W, 0805	CRCW08051K15FKEA	Vishay-Dale	Y	0805
43	Fitted	1	R17	RES, 0.22 ohm, 1%, 0.25W, 1206	ERJ-8RQFR22V	Panasonic	Y	1206
44	Fitted	24	R20, R25, R26, R29, R30, R35, R36, R39, R40, R45, R46, R49, R50, R55, R56, R59, R60, R65, R66, R69, R70, R75, R76, R79	RES, 10k ohm, 5%, 0.125W, 0805	CRCW080510K0JNEA	Vishay-Dale	Y	0805
45	Not Fitted	0	R23, R33, R63, R73	RES, 1.2Meg ohm, 5%, 0.125W, 0805	ERJ-6GEYJ125V	Panasonic	Y	0805
46	Not Fitted	0	R24, R34, R64, R74	RES, 100k ohm, 1%, 0.125W, 0805	ERJ-6ENF1003V	Panasonic	Y	0805
47	Fitted	6	R27, R37, R47, R57, R67, R77	RES, 330k ohm, 0.5%, 0.1W, 0805	RR1220P-334-D	Susumu Co Ltd	Y	0805
48	Fitted	6	R28, R38, R48, R58, R68, R78	RES, 102k ohm, 1%, 0.125W, 0805	CRCW0805102KFKEA	Vishay-Dale	Y	0805
49	Fitted	2	R43, R53	RES, 1.2Meg ohm, 5%, 0.125W, 0805	ERJ-6GEYJ125V	Panasonic	Y	0805
50	Fitted	1	R80	RES, 0 ohm, 5%, 0.25W, 1206	ERJ-8GEY0R00V	Panasonic	Y	1206
51	Fitted	3	T1, T2, T3	Transformer, Push-Pull, 12.8uH, TH	750342312	Wurth Elektronik eiSos	Y	Transformer, 25x16x22.2mm
52	Fitted	1	U1	100V Push-Pull Current Mode PWM Controller, 10-pin MSOP, Pb-Free	LM5030MM/NOPB	Texas Instruments (was National Semiconductor)	Y	MUB10A
53	Fitted	1	U2	1.2V - 8V, 3A PFET Load Switch with Configurable Slew Rate, Fast Transient Isolation and Hysteretic Control, DDC0006A	TPS27082LDDC	Texas Instruments	Y	DDC0006A
54	Fitted	6	U3, U5, U7, U9, U11, U13	5V Micropower Low-Dropout Voltage Regulator, 8-pin Narrow SOIC, Pb-Free	LP2954AIM/NOPB	Texas Instruments (was National Semiconductor)	Y	M08A

Table 2. BOM (continued)

SL. NO.	FITTED	QUANTITY	DESIGNATOR	DESCRIPTION	PARTNUMBER	MANUFACTURER	ROHS	PACKAGE REFERENCE
55	Fitted	6	U4, U6, U8, U10, U12, U14	IC, -3V to -36V, -200mA, Ultralow Noise, High-PSRR LDO Negative Linear Regulator	TPS7A30xxDGN	TI		MSOP-8
56	Fitted	1	Z1	Diode, Zener, 12V, 500mW, SOD-123	MMSZ5242B-TP	Micro Commercial Co	Y	SOD-123

7.3 PCB Layout

Note that the total dimension of the board (including all power supply for all three arms of the inverter) is 120 mm x 100 mm.

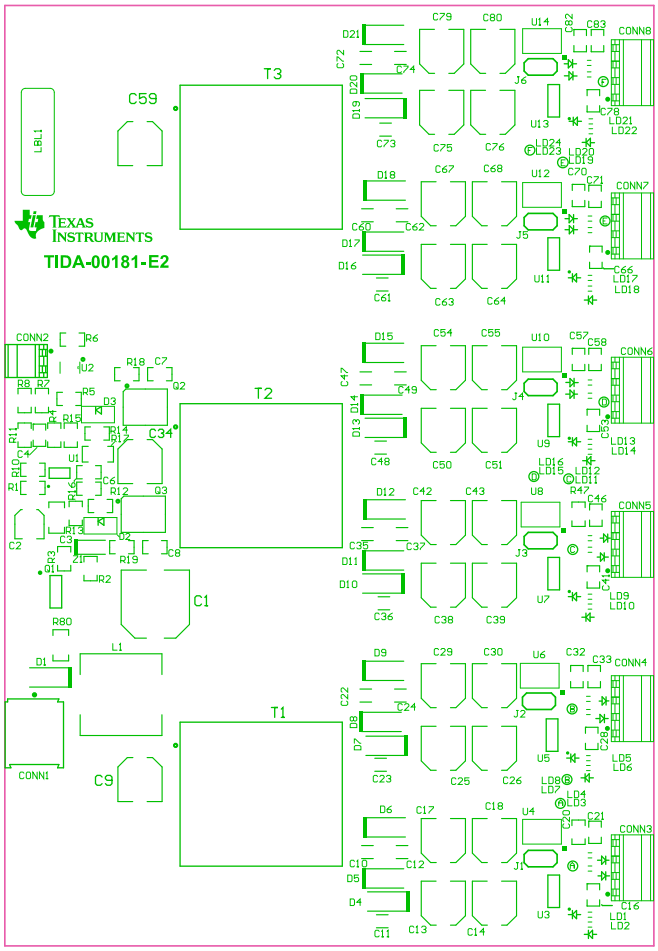


Figure 41. Top Overlay

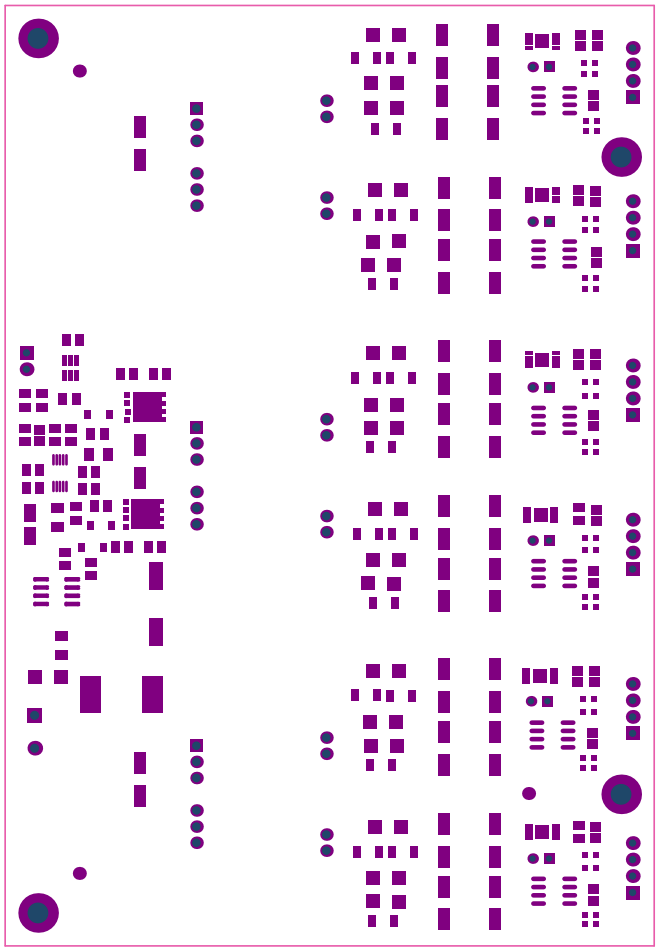


Figure 42. Top Solder Mask

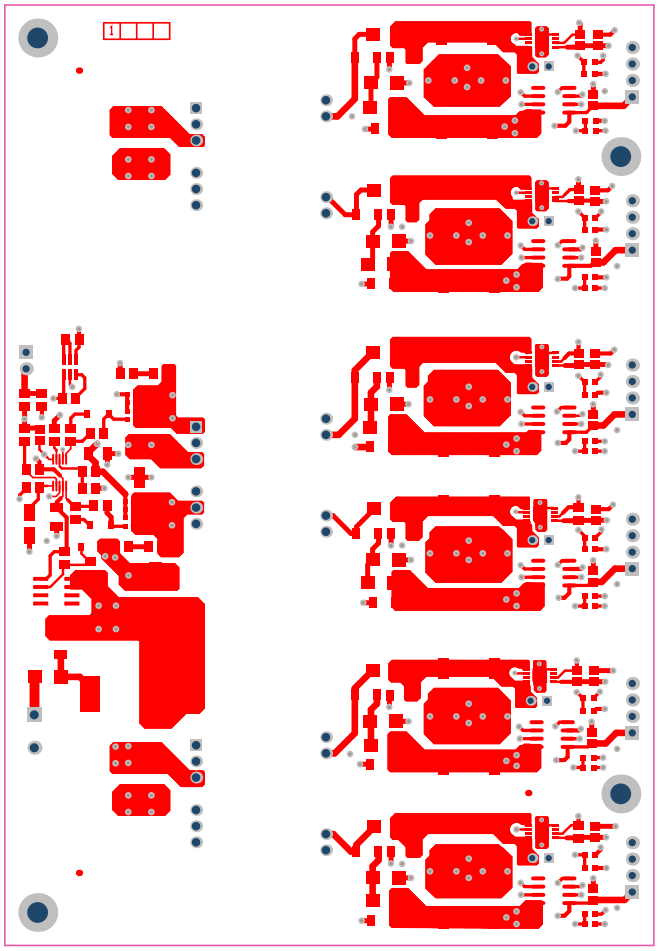


Figure 43. Top Layer

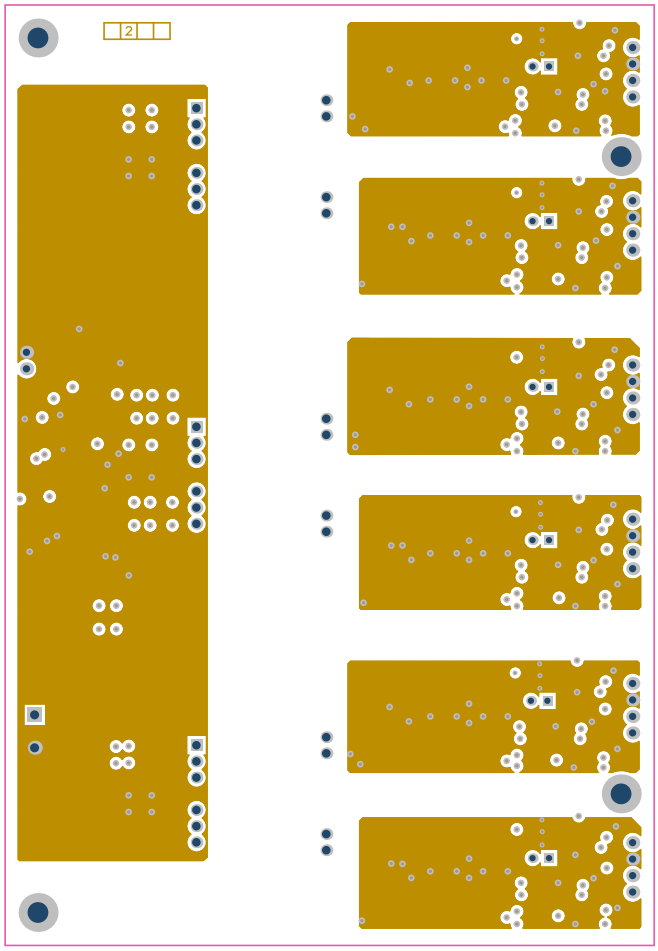


Figure 44. MidLayer1

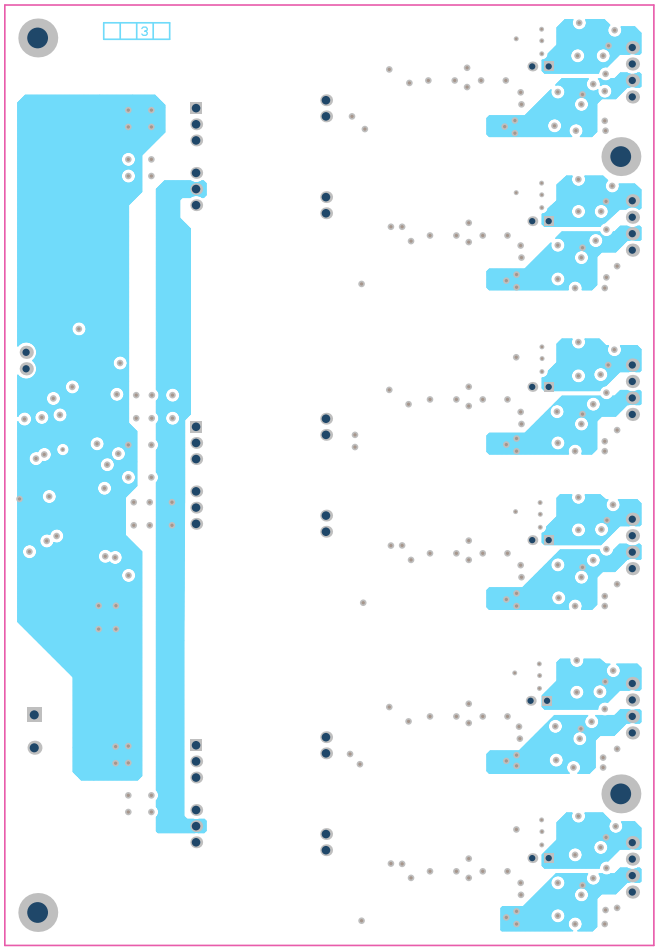


Figure 45. MidLayer2

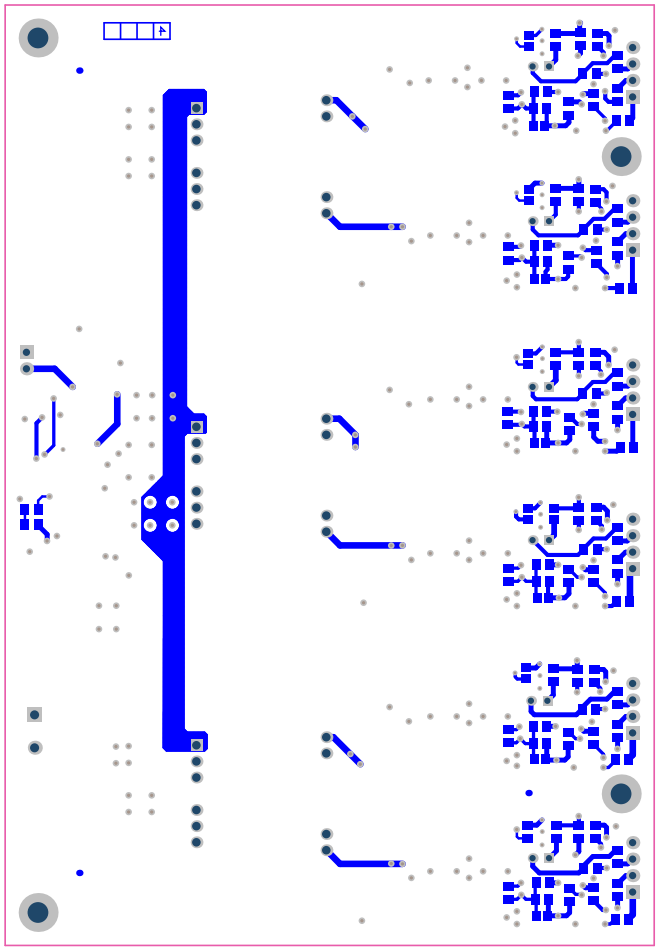


Figure 46. Bottom Layer

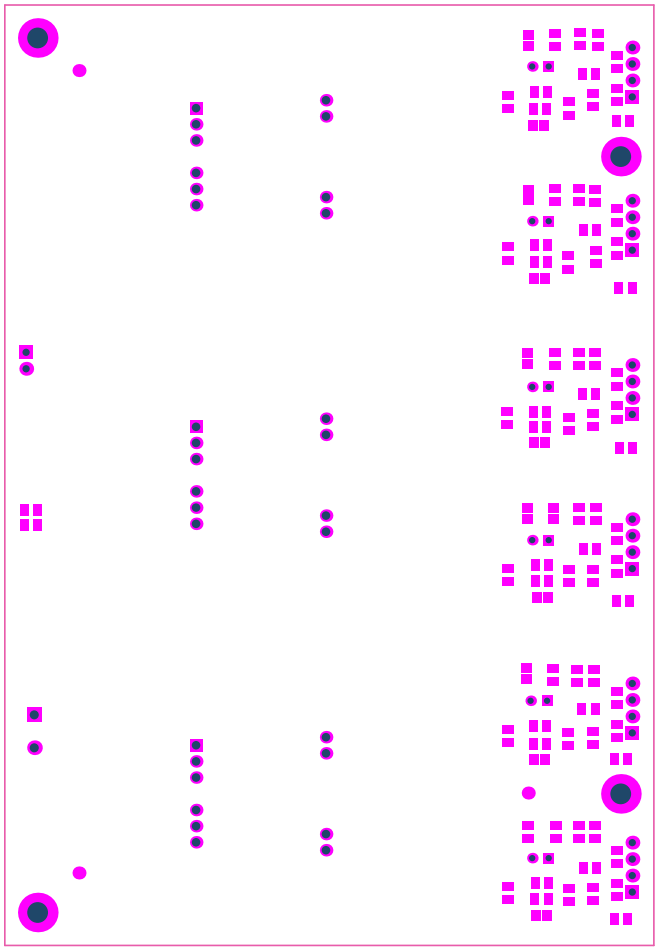


Figure 47. Bottom Solder Mask

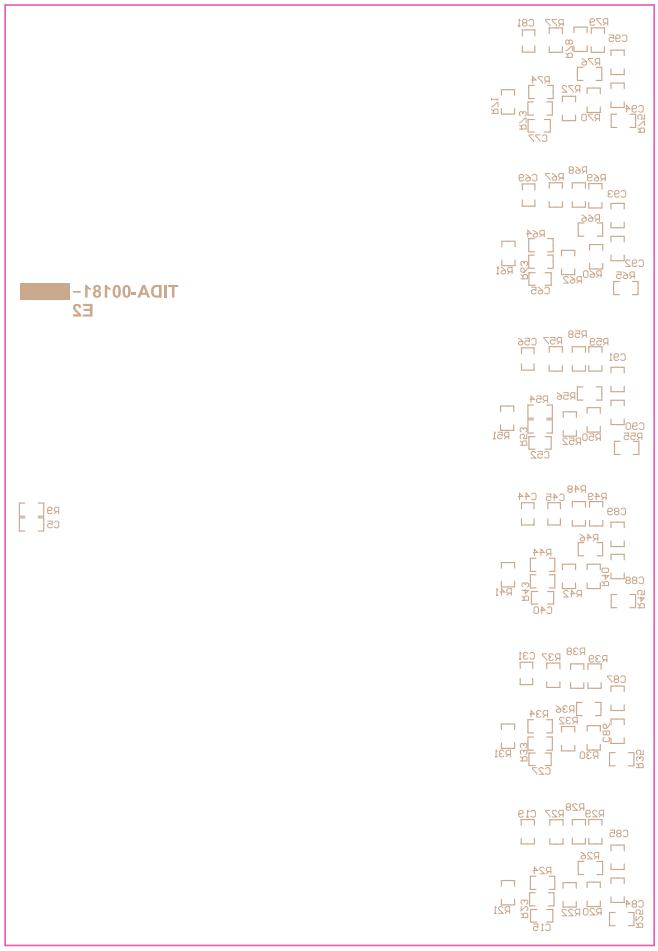


Figure 48. Bottom Overlay

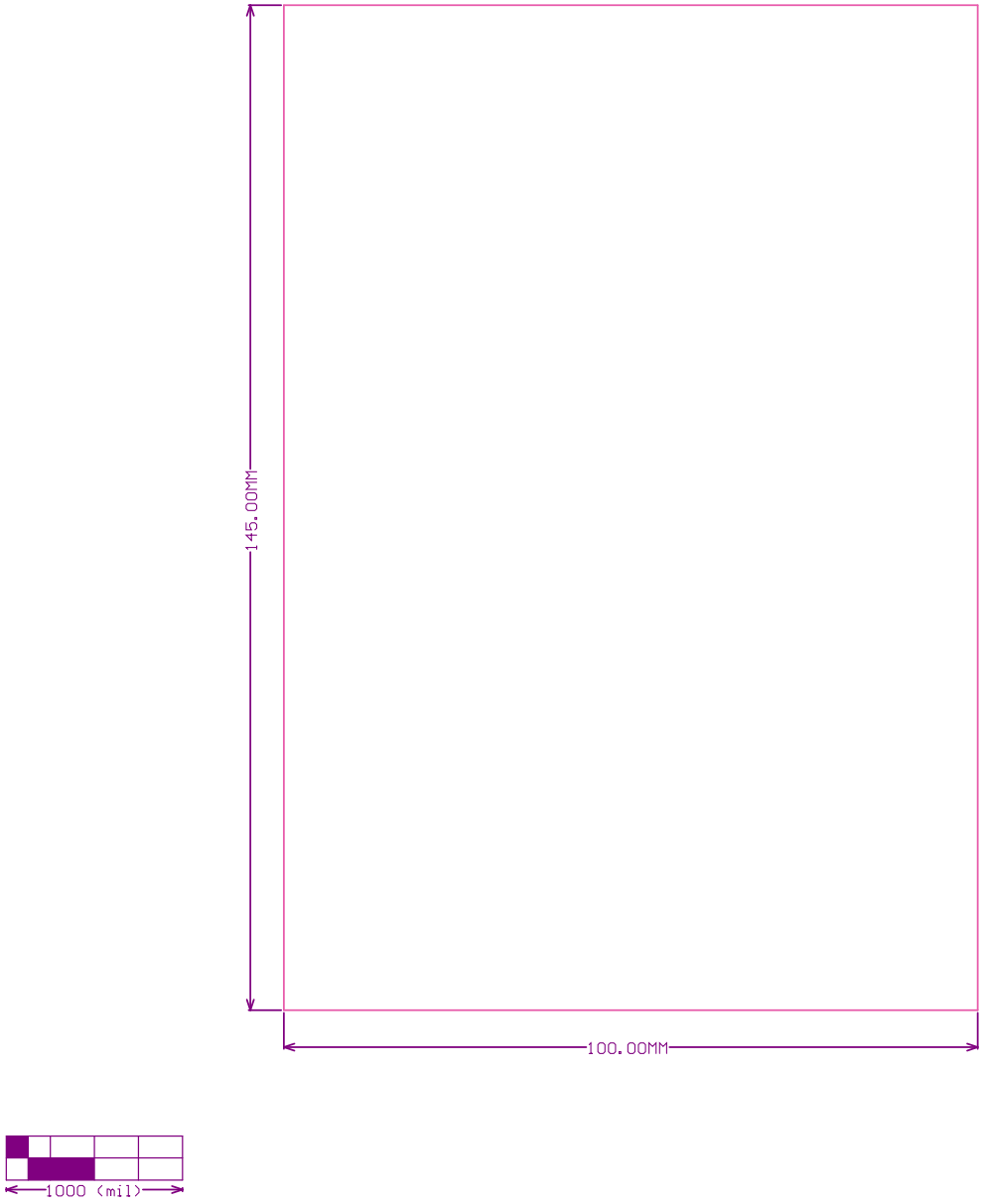


Figure 49. Board Dimensions

7.4 Altium Project

To download the Altium files, see the design files at TIDA-00181.

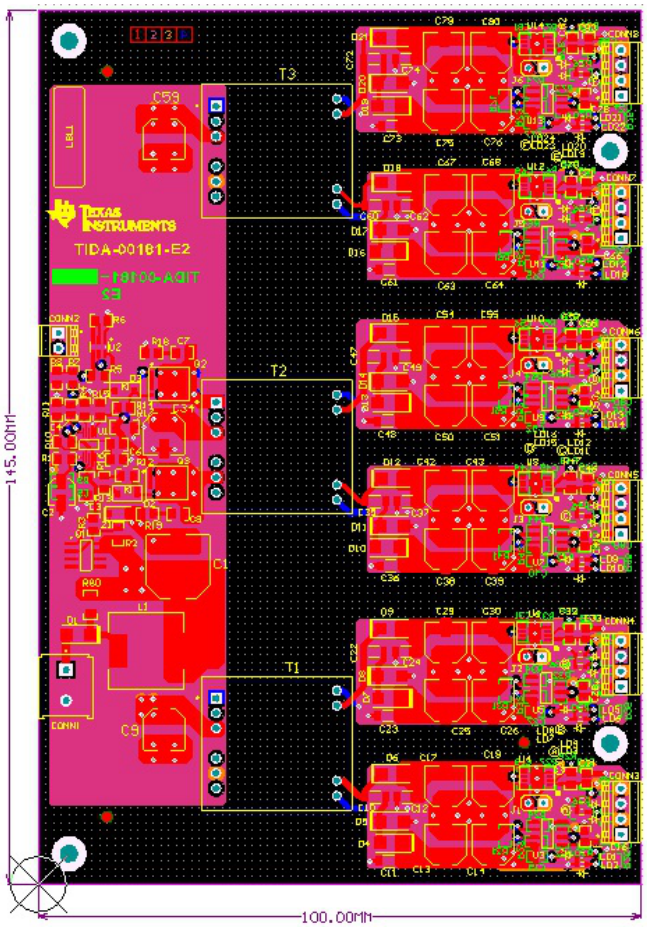


Figure 50. Altium All Layers

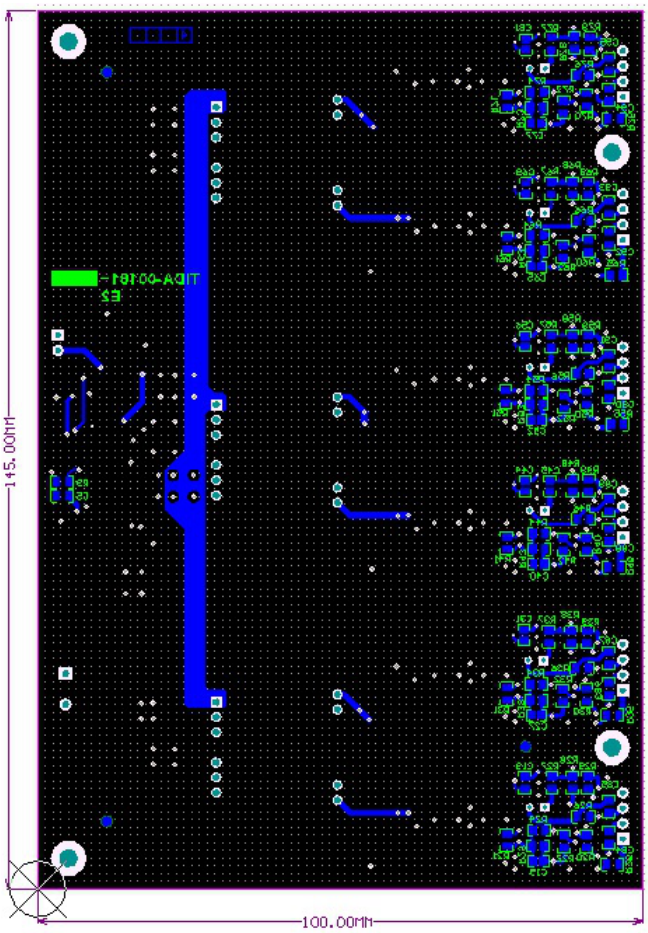


Figure 51. Altium Bottom Layer

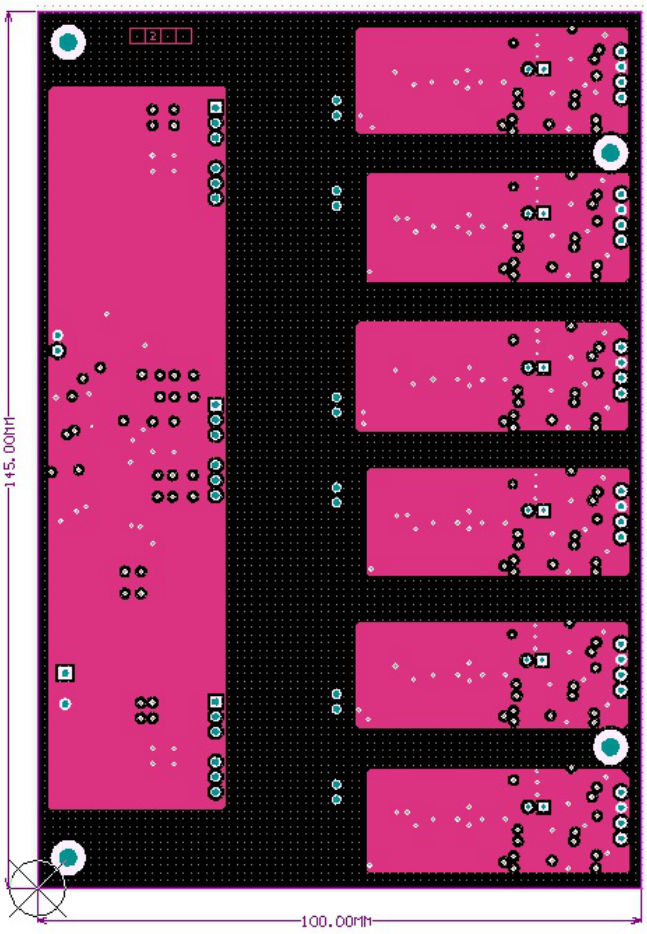


Figure 52. Altium Mid Layer 1

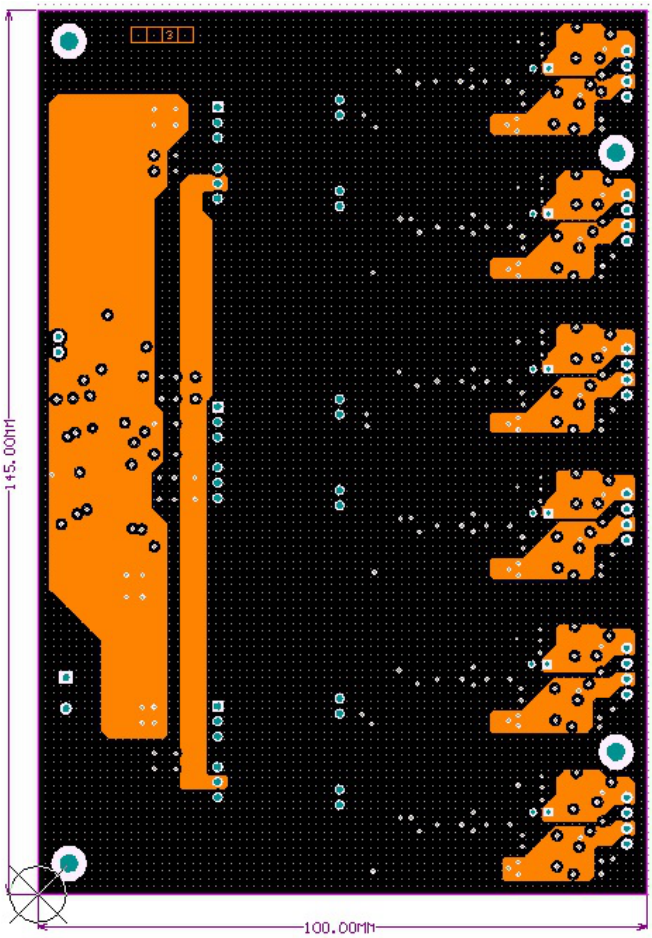


Figure 53. Altium Mid Layer 2

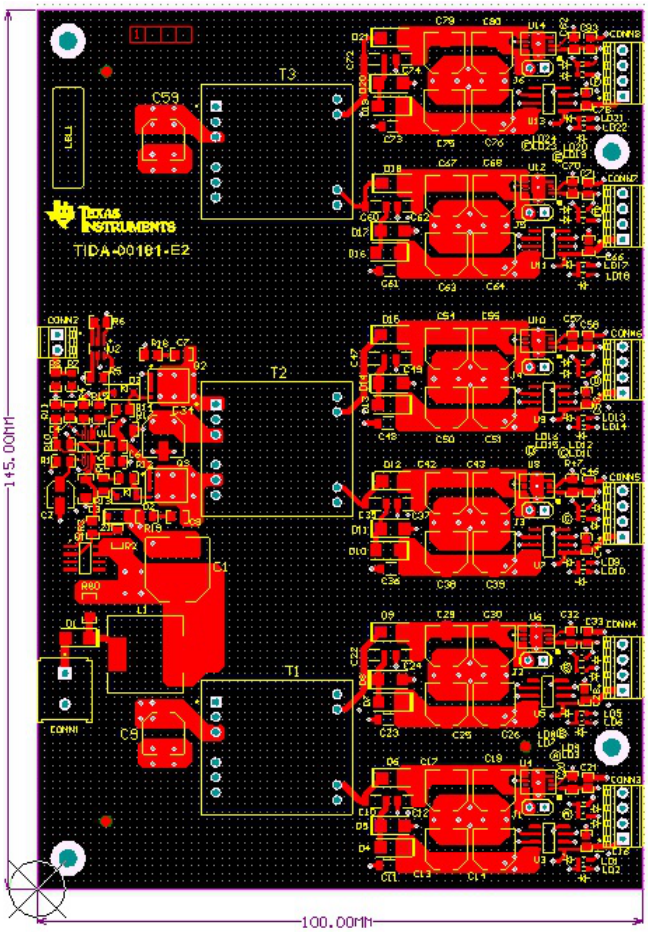


Figure 54. Altium Top Layer

7.5 Gerber Files

To download the Gerber files, see the design files at TIDA-00181.

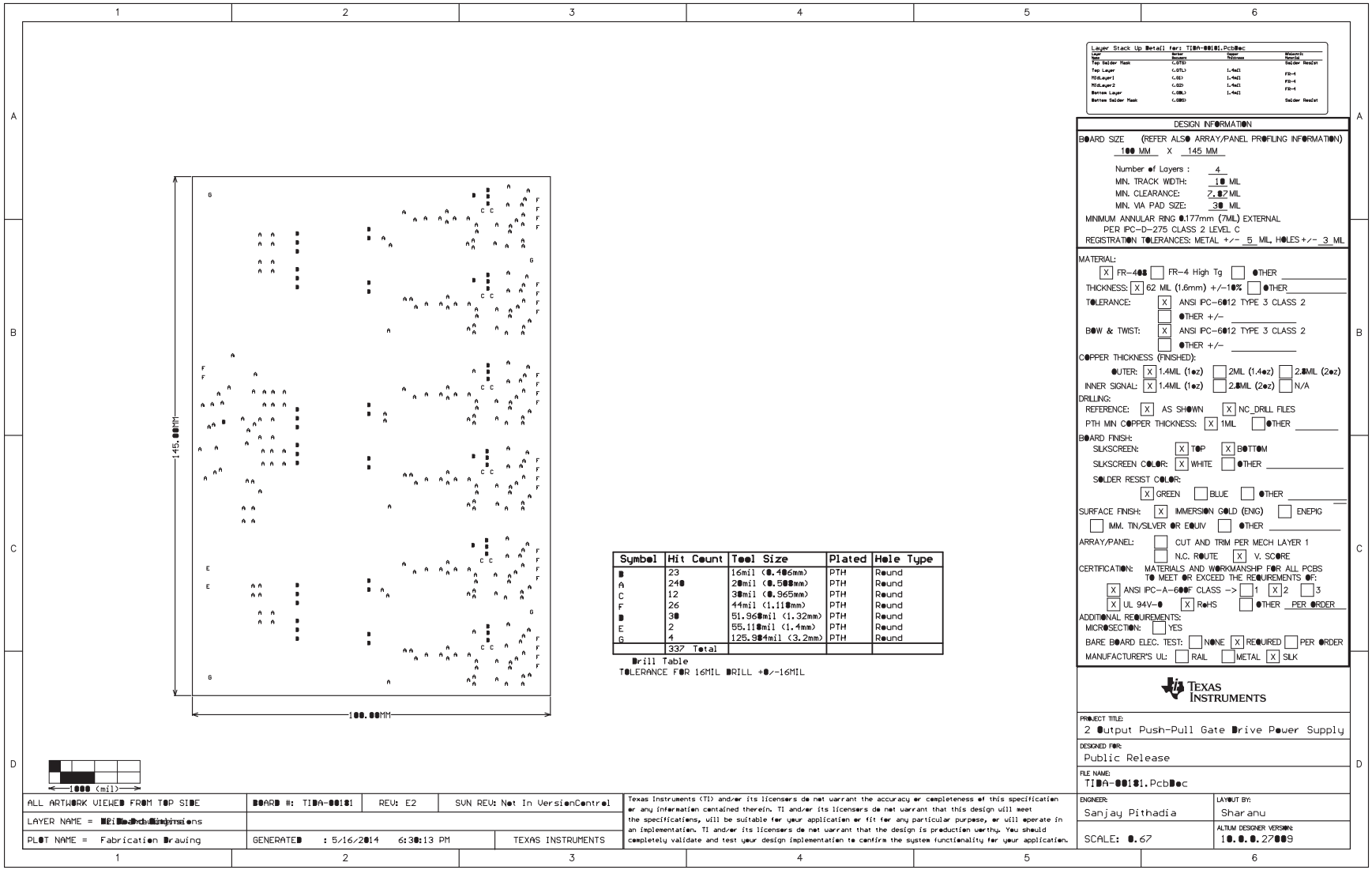


Figure 55. Fabrication Drawing

7.6 Assembly Drawings

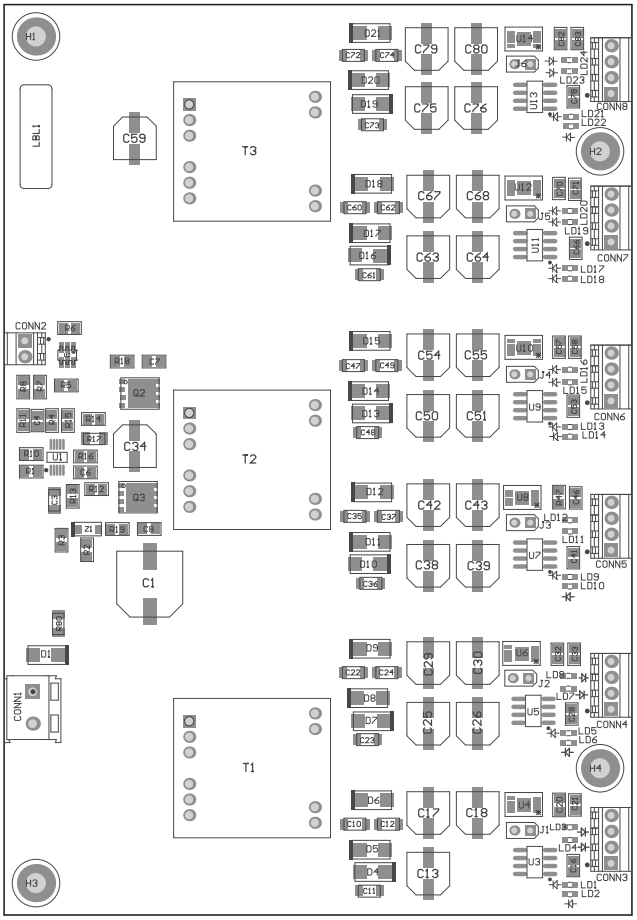


Figure 56. Top Assembly Drawing

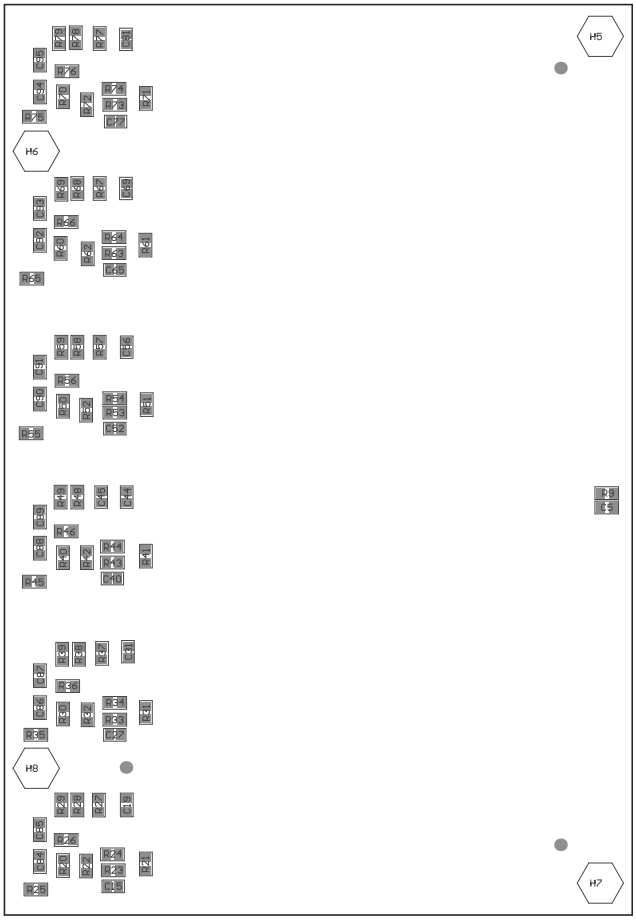


Figure 57. Bottom Assembly Drawing

8 References

1. LM5030 Data Sheet, *LM5030 100 V Push-Pull Current Mode PWM Controller* (SNVS215).
2. LP2954/LP2954A Data Sheet, *LP2954/LP2954A 5 V and Adjustable Micropower Low-Dropout Voltage Regulators* (SNVS096).
3. TPS7A3001 Data Sheet, *TPS7A3001 –36 V, –200 mA, Ultralow-Noise, Negative Linear Regulator* (SBVS125).

9 About the Author

SANJAY PITHADIA is a Systems Engineer at Texas Instruments where he is responsible for developing subsystem design solutions for the Industrial Motor Drive segment. Sanjay has been with TI since 2008 and has been involved in designing products related to Energy and Smart Grid. Sanjay brings to this role his experience in analog design, mixed signal design, industrial interfaces and power supplies. Sanjay earned his Bachelor of Technology in Electronics Engineering at VJTI, Mumbai.

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Revision A History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Changes from Original (June 2014) to A Revision	Page
• Changed the bottom winding of the transformer secondary side	1
• Changed the bottom winding of the transformer secondary side	6

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