TDINV3500P100: 3.5kW Inverter Evaluation Board

Introduction

The TDINV3500P100_0v1 3.5kW inverter kit provides an easy way to evaluate the performance advantages of GaN power FETs in various inverter applications, such as solar and uninterruptible power supplies (UPS). The kit provides the main features of a single-phase inverter in a proven, functional configuration, operating at or above 100kHz. At the core of the inverter are four TP90H180PS 170mΩ GaN FETs configured as a full bridge. These are tightly coupled to gate-drive circuits on a board which also includes flexible microcontroller options and convenient communication connection to a PC. The switch-mode power signals are filtered to provide a pure sinusoidal output. For more information and the complete design files, please visit transphormusa.com/pv35kit. **The TDINV3500P100-KIT is for evaluation purposes only.**
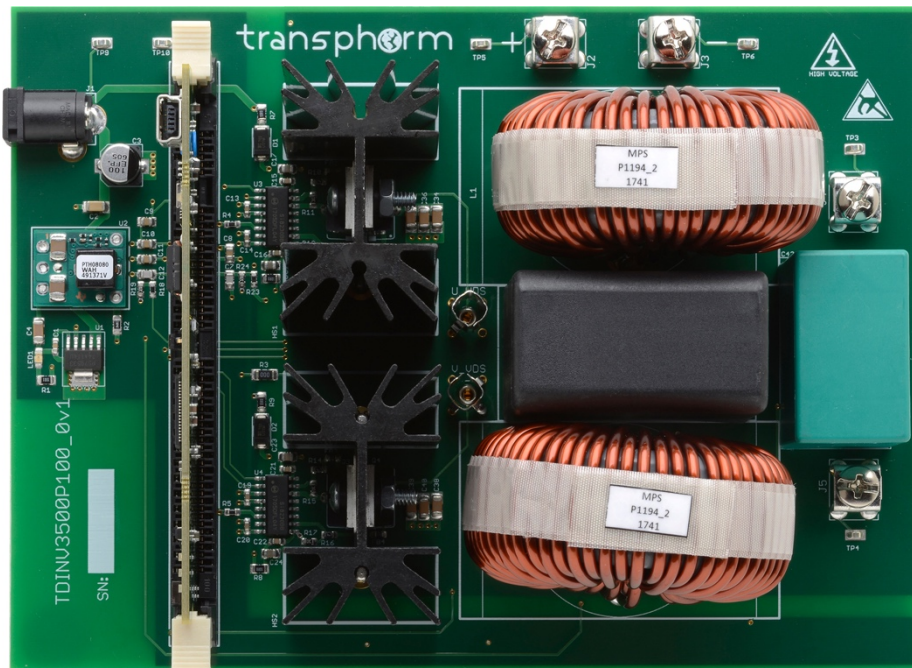

Figure 1. TDINV3500P100_0v1 inverter evaluation board

Warning

This evaluation board is intended to demonstrate GaN FET technology and is for demonstration purposes only and no guarantees are made for standards compliance.

There are areas of this evaluation board that have exposed access to hazardous high voltage levels. Exercise caution to avoid contact with those voltages. Also note that the evaluation board may retain high voltage temporarily after input power has been removed. Exercise caution when handling.

When testing converters on an evaluation board, ensure adequate cooling. Apply cooling air with a fan blowing across the converter or across a heatsink attached to the converter. Monitor the converter temperature to ensure it does not exceed the maximum rated per the datasheet specification.

The control portion of the circuit is designed around the popular C2000™ family of microcontrollers from Texas Instruments (TI). The source code is available along with related support information directly from TI. In addition to this general resource, Transphorm provides original firmware which comes loaded in flash on the microcontroller. The source code, configured as a complete project, is available at transphormusa.com/pv35kit. This project is a convenient starting point for further developments. The microcontroller itself resides on a small, removable control card, supplied by TI, so that different C2000 devices may be used if desired. The schematic for the TDINV3500P100 circuit board is provided at the end of this user guide document, as well in the design files.

The TDINV3500P100-KIT includes:

- TDINV3500P100 single-phase inverter assembly
- Texas Instruments F28035 control card
- 12V power supply with U.S. adaptor

Complete design files, firmware files and support documentation can be found online at transphormusa.com/pv35kit.

TDINV3500P100 input/output specifications

- High-voltage input: $750V_{DC}$ max
- Auxiliary supply (J1): $12V_{CC}$
- Input: $0V_{DC}$ - $750V_{DC}$
- Output: $V_{DC} / \sqrt{2}V_{RMS}$ at 50/60Hz [1], up to 3500W
- PWM frequency: 50kHz - 150kHz [2]
- Power dissipation in the GaN FET is limited by the maximum junction temperature. Refer to the TP90H180PS datasheet

[1] The output frequency may be changed in the software; as delivered it is 60Hz

[2] The switching frequency may be changed in the software; as delivered it is 100kHz

Circuit description

Refer to Figure 2 for a block diagram of the inverter circuit. A detailed schematic is available in the design files.

The TDINV3500P100 inverter is a simple full-bridge inverter. Two GaN half-bridges are driven with pulse-width modulated (PWM) command signals to create the sinusoidally varying output. The output filter largely removes the switching frequency, leaving the 50/60Hz fundamental sinusoid. The high-frequency (100kHz+) PWM signals are generated by the TI microcontroller and connected directly to high speed, high voltage gate drivers. A connection for external communication to the microcontroller is provided by an isolated USB interface. Except for the high-voltage supply for the power stage, all required voltages for the control circuitry are derived from one 12V input.
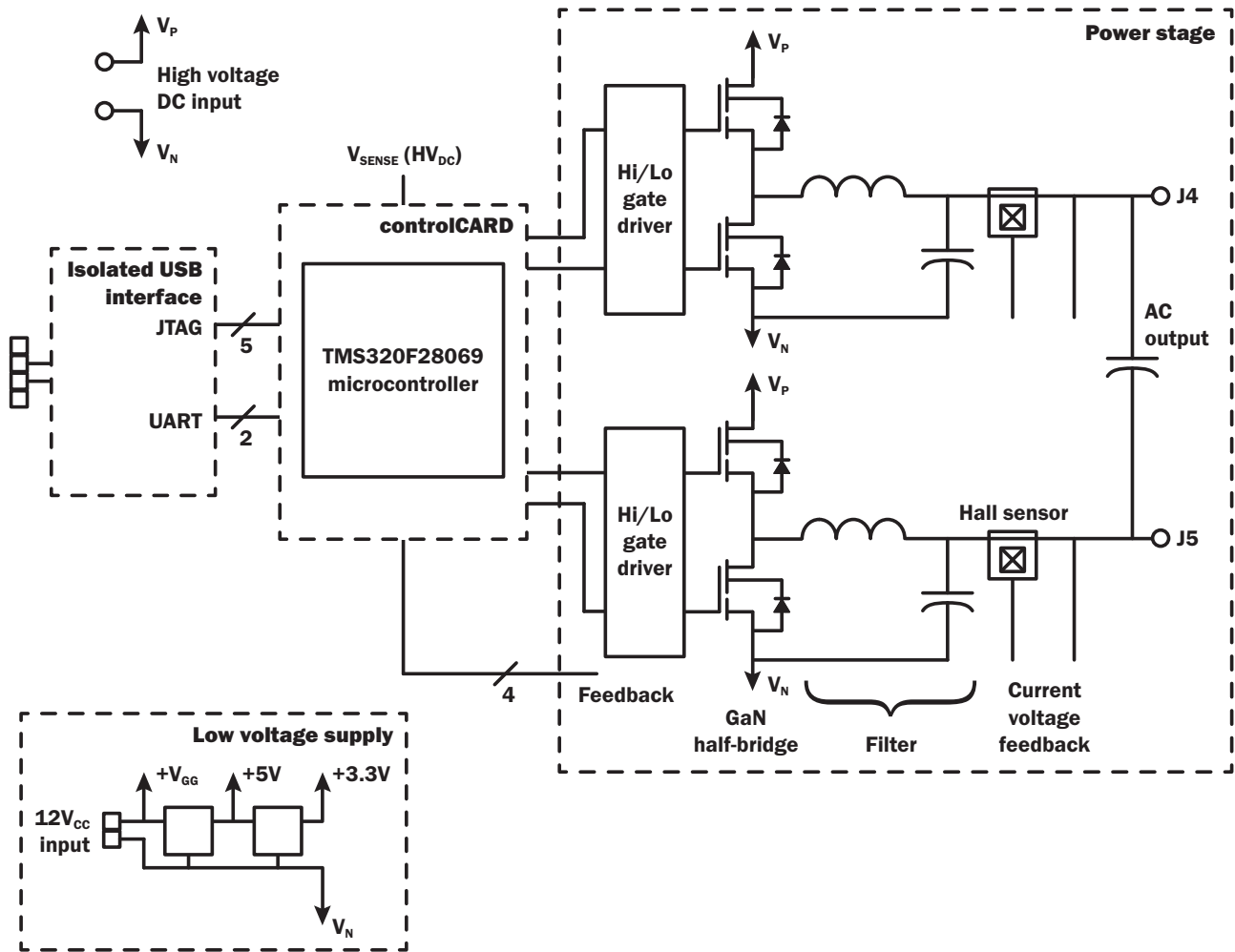
Figure 2. Circuit block diagram

The inverter takes advantage of diode-free operation, in which the freewheeling current is carried by the GaN FETs themselves due to their bi-directional capability, without the need of additional freewheeling diodes. For minimum conduction loss, the gates of the FETs are enhanced while they carry the freewheeling current. The high and low-side V_{GS} waveforms are therefore pairs of non-overlapping pulses, as illustrated in Figure 3 below.
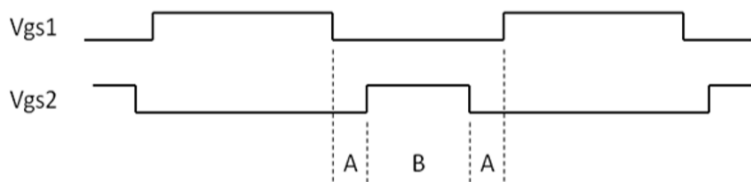
Figure 3. Non-overlapping gate-drive pulse; A is a dead time set in the firmware

Gate drivers

High-voltage integrated drivers supply the gate-drive signals for the high and low-side GaN FETs. These are 2500V isolation drivers (Silicon Labs Si823x family), specifically chosen for high-speed operation without automatic dead time insertion. The dead time between turn-off of one GaN FET in a half-bridge and turn-on of its mate is set in the firmware.

Dead time control

The required form of the gate-drive signals is shown in Figure 3. The times marked A are the dead times when neither transistor is driven on. The dead time must be greater than zero to avoid shoot-through currents. The Si8230 gate drive chip ensures a minimum dead time based on the value of resistor R24, connected to the AC input. The dead time in ns is equal to the resistance in kΩ x 10, so the default value of 5.76k corresponds to 57.6ns. This will add to any dead time already present in the input signals. The on-board pulse generator circuit; for example, creates dead times of about 100ns (see Figure 6). The resulting dead time at the gate pins of Q1 and Q2 is about 60ns. Either shorting or removing R4, R5 will reduce the dead time to 60ns.

Output filter

A simple LC filter on the output (L1, L2, C43 and C44) attenuates the switching frequency, producing a clean sinusoidal waveform for output connections in terminals J4 and J5. The filter inductors and capacitors used on the demo board were chosen to provide the optional combination of benefits: low loss, good attenuation of the switching frequency, and small size. Consult the schematic and/or bill of materials to verify values; but in general, the cutoff frequency will be around 5kHz - 10kHz to accommodate 100Hz switching. The inductors have powder cores with relatively low permeability (60-90) and soft saturation characteristics. The inductors and/or capacitors can be changed to evaluate different filter designs.

Current sensing

Hall sensors U5 and U6 provide linear current feedback to the microcontroller. These signals are used to control output power flow, to protect against over current. Note that these are placed at an intermediate point of the output filter. Refer to the bill of materials on page 7 to confirm the sensor part numbers, but typical would be the Allegro ACS723-20A sensor, which has a ±20A range (100mV/A). These parts are pin-compatible with a ±5A and ±30A versions of ACS723, should higher or lower ranges be desired. Note also that resistor dividers scale the 5V outputs for the 3V range of the A/D.

Communication

Communication between the microcontroller and a computer is accomplished with a mini USB cable to a JTAG microcontroller interface.

Control card

The microcontroller resides on a removable card, which inserts in a DIM100 socket on the inverter PCB. The socket can accept many of the C2000 series control cards from Texas Instruments. The TMDSCNCD28035 Piccolo control card supplied with the kit provides capability to experiment with a wide variety of modulation and control algorithms. It comes loaded with firmware to allow immediate, out-of-the-box, operation. Should the user wish to use an alternative microcontroller family, an appropriate control card can be designed to insert into the DIM100 socket.

Heatsink

The two TO-220 GaN FETs on each half-bridge are mounted on a common heatsink. The heatsink is adequate for 3500W operation with forced air flow. Even higher efficiency at high power may be achieved by minimizing the temperature rise. This may be accomplished with stronger airflow. Alternately the heatsinks could be replaced with larger and more effective ones.

Connections

Power for the AC output is derived from the high-voltage DC input. This will typically be a DC power supply with output voltage up to 750V_{DC}. A 20μF, low ESR film capacitor is provided as a bypass capacitor for the high voltage supply, along with several lower valued ceramic capacitors in parallel. This is not intended to provide significant energy storage. It is assumed that the power supply or preceding DC-DC stage contains adequate output capacitance.

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

Note that all signals on the board are referenced to the negative terminals of the high and low voltage supplies, which are tied together on the PCB. The heatsinks are also connected to the negative terminals of the supplies.

Powering on the board

- Refer to Figure 4. Insert the microcontroller card to the DIM100 socket before applying any power to the board.
- Before turning on the supply, connect the high-voltage power supply to the +/- inputs (J2 and J3). **DO NOT apply too much force to the J2 and J3 connectors, as excessive force may bend and/or crack the PCB.**
- If a load is to be used, connect the load to the output terminals (J4 and J5). **DO NOT apply too much force to the J4 and J5 connectors, as excessive force may bend and/or crack the PCB.**
- Insert the V_{CC} (12V) plug to jack J1. LED1 should illuminate, indicating power is applied to the 5V and 3.3V regulators. Depending on the specific control card used, one or more LEDs on the control card will also illuminate, indicating power is applied. A flashing LED indicates the firmware is executing.
- To use the pre-loaded firmware, no computer connection is required. If a computer connection is required for code modification, connect the USB cable from the computer to the USB connector on the microcontroller.
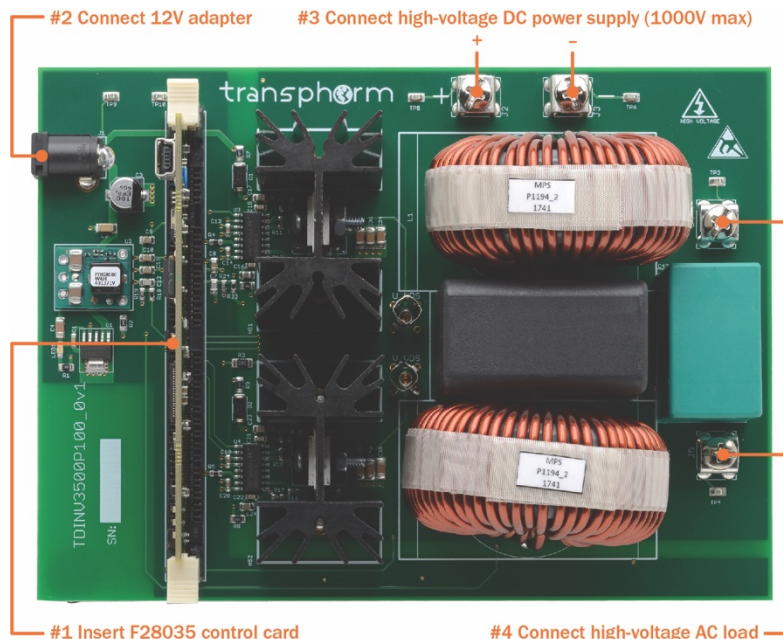- Turn on the high-voltage power. The high-voltage supply may be switched ON instantly or raised gradually.

Figure 4. Connections

Powering off the board

1. Switch off high-voltage DC supply
2. Power off 12V aux supply

Test overview

Figure 5 shows typical waveforms. The negative terminal of the high-voltage supply is a convenient reference for the oscilloscope measurements, provided there are not multiple connections to earth ground.
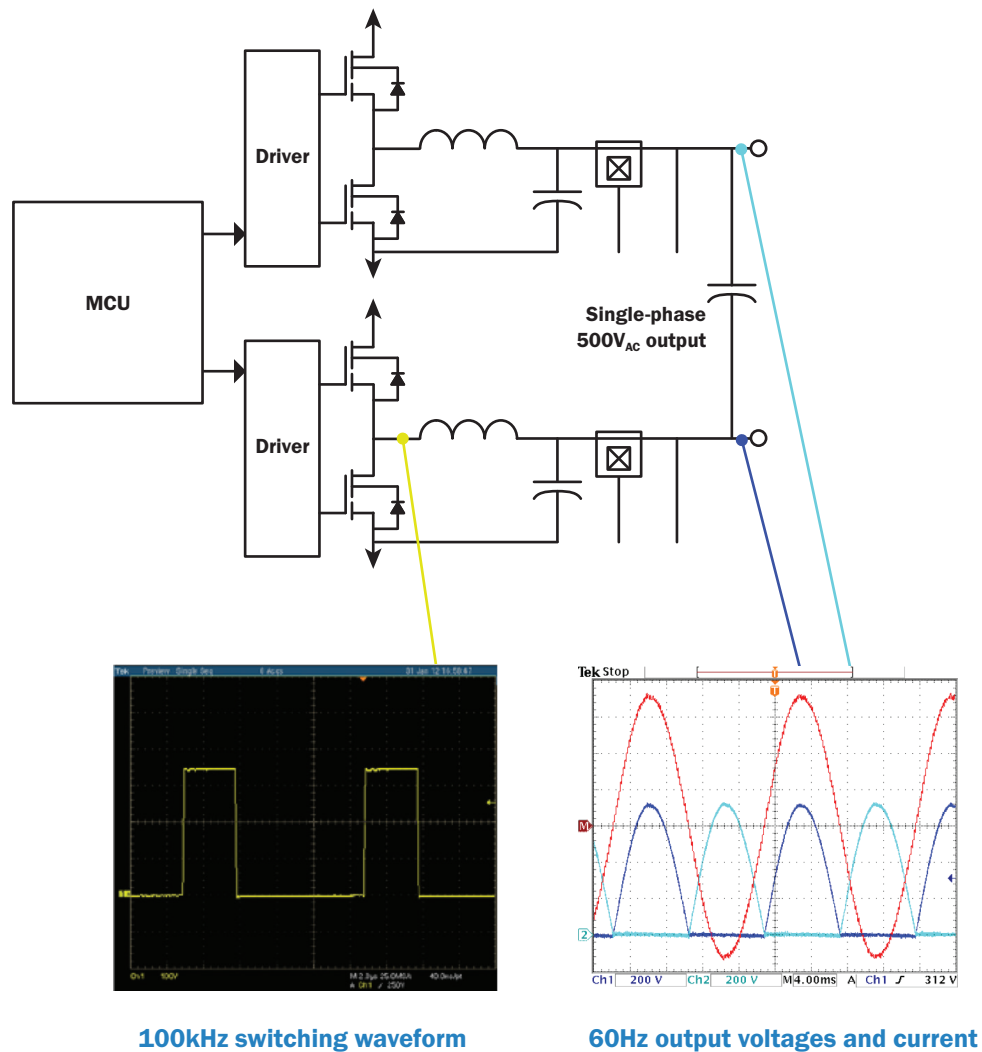

100kHz switching waveform   **60Hz output voltages and current**

Figure 5. Typical waveforms

Typical efficiency results are shown in Figure 6. These data points correspond to efficiency measurements made in still air with 20 minutes' dwell at each power level. Input power from the $750V_{DC}$ source and output power to a resistive load were measured with a Yokogawa WT1800 power analyzer.
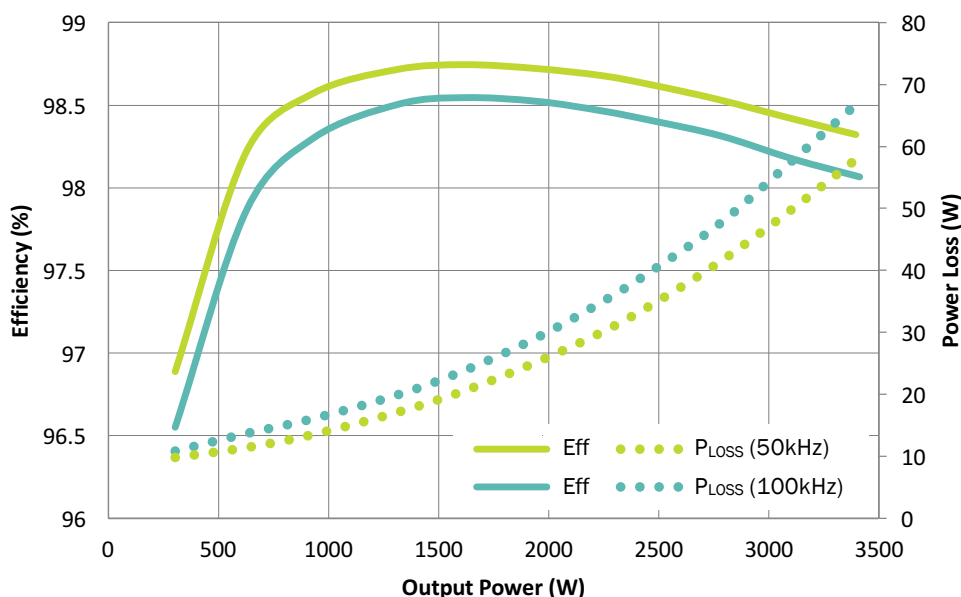
Figure 6. Typical efficiency: $720V_{DC}$ input, $500V_{AC}$ output

Design details

See Figures 7 and 8 for a detailed circuit schematic and Figure 9 for the PCB layers (also included in the design files). The parts list can be found in Table 1.

**Table 1. TDINV3500P100 evaluation board bill of materials (BOM)**

Designator	Qty	Value	Descriptor/Package	Manufacturer Part Number	Manufacturer
HS1, HS2	2		529802B02500G	529802B02500G	Aavid Thermalloy
J2, J3, J4, J5	4		KEYSTONE_7691	7691	Keystone
LED1	1		LEDCHIP-LED0805	SML-211UTT86	ROHM Semiconductor
J1	1		PJ-002AH	PJ-002AH	CUI
U_VDS, V_VDS	2		TEKTRONIX-PCB	131-4353-00	Tektronix
TP1, TP2, TP3, TP4, TP5, TP6, TP7, TP8, TP9, TP10	10		TESTPOINT-KEYSTONE5015	5015	Keystone
C1, C13, C14, C15, C16, C19, C20, C21, C22, C25, C27	11	0.1µF	C-USC0603	06033C104JAT2A	AVX
C8, C9, C10, C11	4	0.1µF	C-USC0805	08053C104KAT2A	AVX
C5, C43, C44	3	0.1µF	C-USC2225K	C2225C104KFRACTU	Kemet
C37, C41	2	0.1µF	C-EUC1812	C1812V104KDRACTU	Kemet
R3	1	0Ω	R-US_R1206	ERJ-8GEY0R00V	Panasonic
R33, R34, R35, R36, R37, R38, R39, R40	8	1.6MΩ	R-US_R1206	ERJ-8ENF1604V	Panasonic
R6, R7, R8, R9	4	10Ω	R-US_R0805	ERJ-6GEYJ100V	Panasonic
RFB1, RFB2	2	10Ω	R-US_R1206	RNCP1206FTD10R0	Stackpole
R19, R24	2	10.2kΩ	R-US_R0603	ERJ-3EKF1022V	Panasonic
C31, C32	2	100nF	C-EUC1206	CL31F104MBCNNNC	Samsung Electro-

Designator	Qty	Value	Descriptor/Package	Manufacturer Part Number	Manufacturer
					Mechanics
C33	1	100pF (10v)	C-USC0603	885012006008	Wurth Electronics
C3	1	100µF	PANASONICFPV	EEE-FPE101XAP	Panasonic
R11, R13, R15, R17	4	10kΩ	R-US_R0603	ERJ-3GEYJ103V	Panasonic
R41, R42, R43, R44, R51	5	10kΩ	R-US_R1206	RC1206FR-0710KL	Yageo
C34, C35, C36, C38, C39, C40	6	10nF / 1200V	C-EUC1206	GRM31CR73A103KW03L	Murata
C17, C18, C23, C24	4	10µF	C-EUC0805	C0805C106M4PACTU	Kemet
C4	1	10µF	C-USC1206	CL31A106KAHNNNE	AVX
FB1, FB2, FB3, FB4	4	120Ω	FB0603	FBMH1608HL121-T	Taiyo Yuden
RSN1, RSN2, RSN3, RSN4	4	15Ω	R-US_R1206	RNCP1206FTD15R0	Stackpole
R1	1	1kΩ	R-US_R0805	ERJ-6GEYJ102V	Panasonic
C26, C28	2	1nF	C-USC0603	-	-
C7, C12	2	1nF	C-USC0805	CC0805KRX7R9BB102	Yageo
C29, C30	2	220pF	C-EUC1206	885012008014	Wurth Electronics
CSN1, CSN2, CSN3, CSN4	4	47pF	C-EUC1206	CL31C470JIFNFNE	Samsung Electro-Mechanics
C2	1	22µF	C-USC1206	CL31A226KAHNNNE	Samsung Electro-Mechanics
C42	1	3.3µF	3.3µF	"	
C4AEQBU4330A11J "	Kemet				
DFB1, DFB2, DFB3, DFB4, DFB5, DFB6, DFB7, DFB8	8	30Ω	R-US_R0805	BLM21SN300SZ1D	Murata
R2	1	348Ω	R-US_R0805	ERJ-6ENF3480V	Panasonic
R10, R12, R14, R16	4	4.7Ω	R-US_R0603	ESR03EZPJ4R7	ROHM Semiconductor
L1, L2	2	440µH	440µH	P1194	MPS
R18, R23	2	5.23kΩ	R-US_R0603	ERJ-3EKF5231V	Panasonic
R4, R5	2	5.76kΩ	R-US_R0603	RC0603FR-075K76L	Yageo
R20, R21, R25, R26	4	560kΩ	R-US_R1206	RC1206FR-07560KL	Yageo
R28, R29, R30, R31	4	680kΩ	R-US_R1206	ERJ-P08J684V	Panasonic
U5, U6	2		ACS723	ACS723LLCTR-20AB-T	Allegro Microsystems
CN1	1		DIMM socket	5390213-1	TE Connectivity
C6	1	20µF	20µF	MKP1848C62090JP4	Vishay
U7	1		OP_JC	OPA2350UA/2K5	Texas Instruments
U2	1		PTH08080WAH	PTH08080WAH	Texas Instruments
U3, U4	2		SI8230	SI8230BB-D-IS	Silicon Labs
Q1, Q2, Q3, Q4	4		TP90H180PS	TP90H180PS	Transphorm
U1	1		TPS79533	TPS79533DCQR	Texas Instruments
D1, D2	2		DIODE-DO-214AC	US1M-13-F	Diodes Inc.
	2		Thermal pad between TP90H180PS (Q1, Q3) and heatsink	SP2000-0.015-00-54	Berquist
	2		Screw on TP90H180PS to heatsink	9902	Keystone
	2		Nut to mount TP90H180PS to heatsink	9600	Keystone
	4		Nylon washer shoulder in between screw/nut and TP90H180PS	3049	Keystone
	5		Bumper to be placed under PCB (5 locations: 4 each corner, 1 in the middle)	SJ-5003(BLACK)	3M
	1		12Vdc aux supply	SMI6-12-K-P5	CUI
	1		Control card	TMDSCNCD28035ISO	Texas Instruments
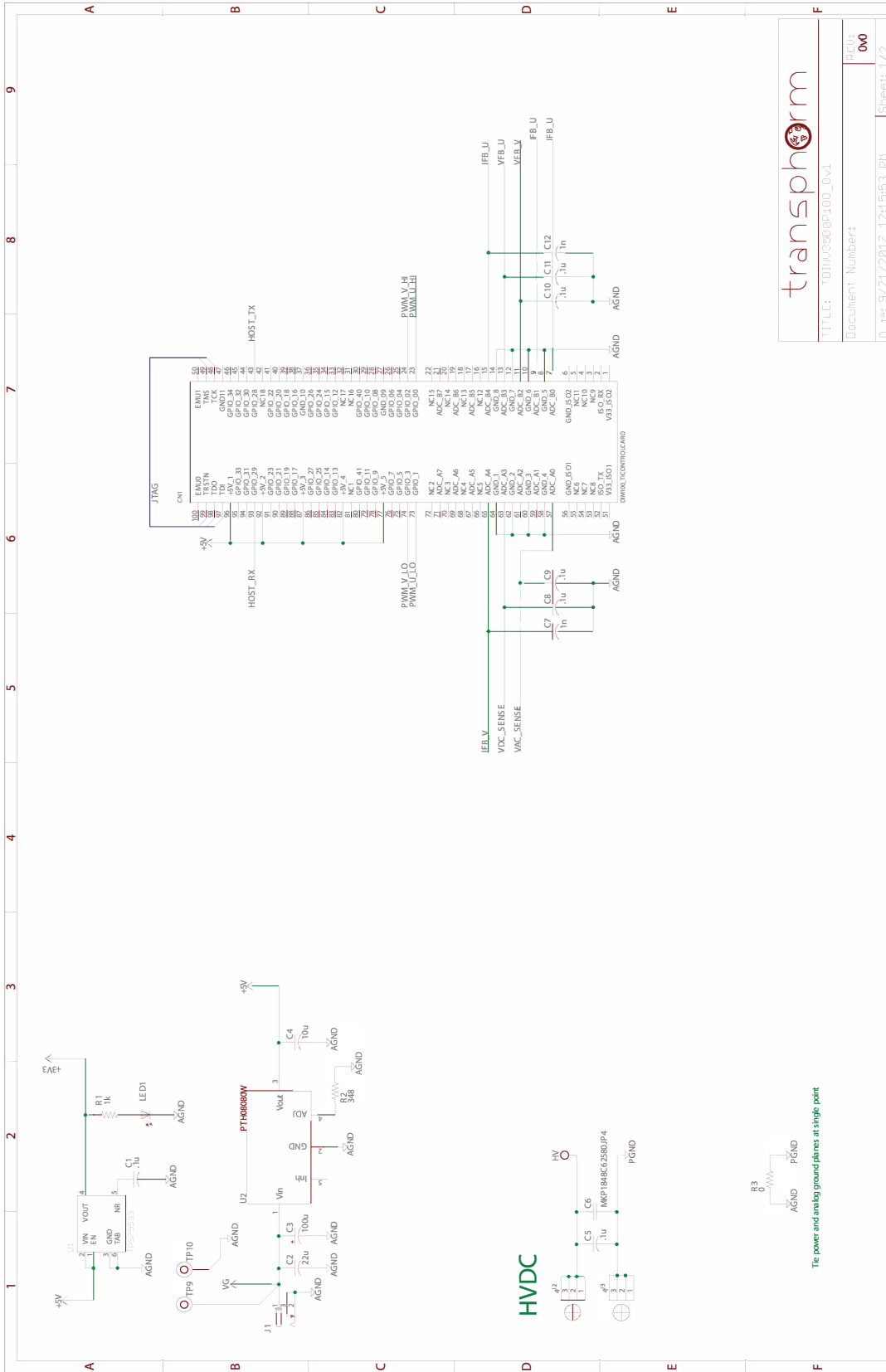
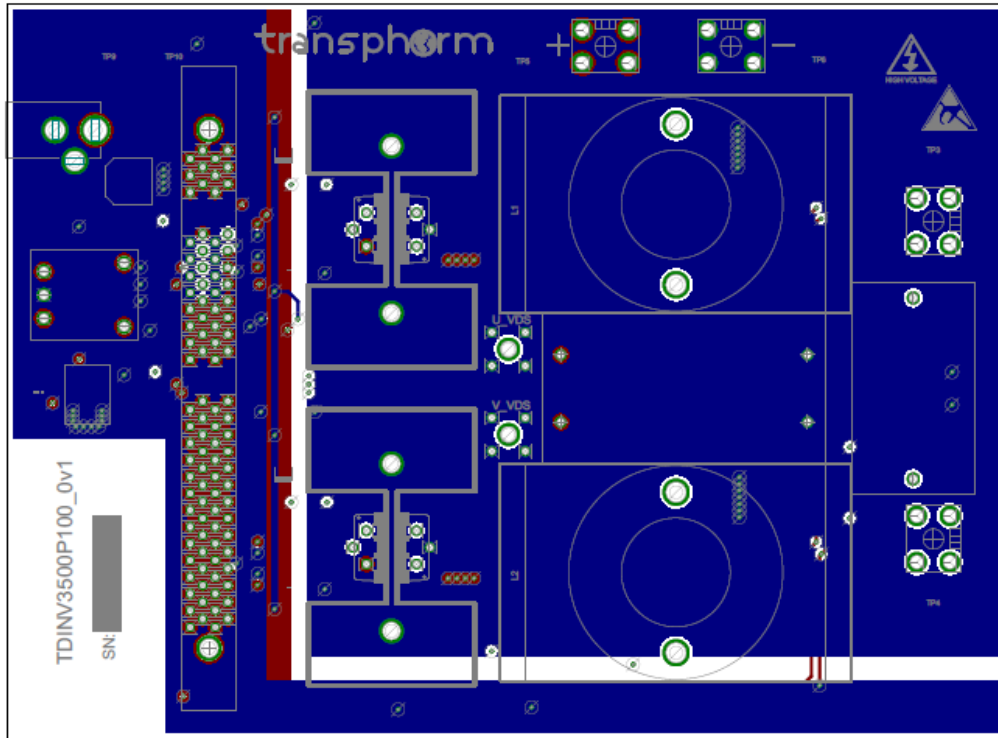**Figure 7. Detailed circuit schematic (1 of 2)**
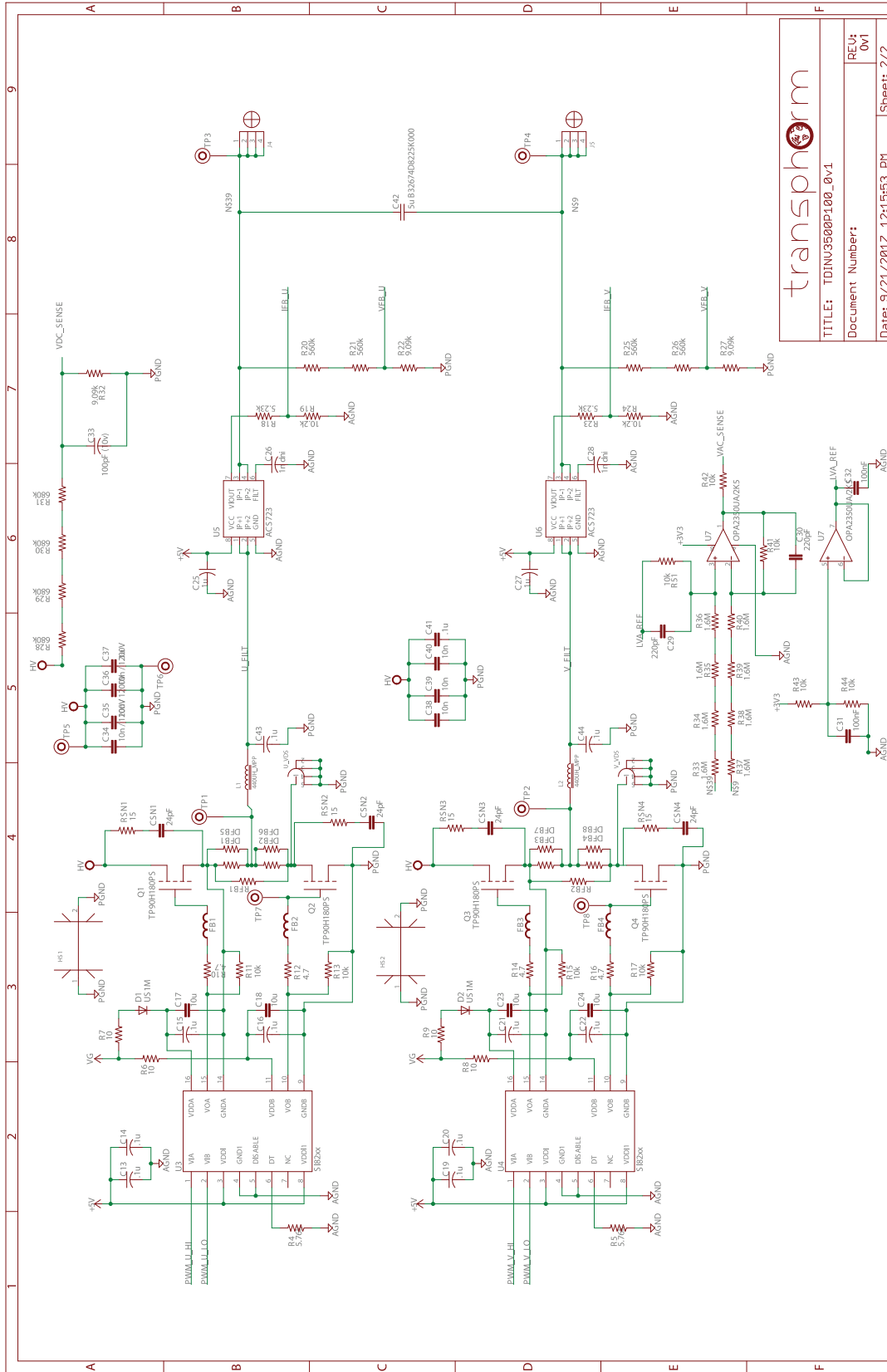
Figure 8. Detailed circuit schematic (2 of 2)
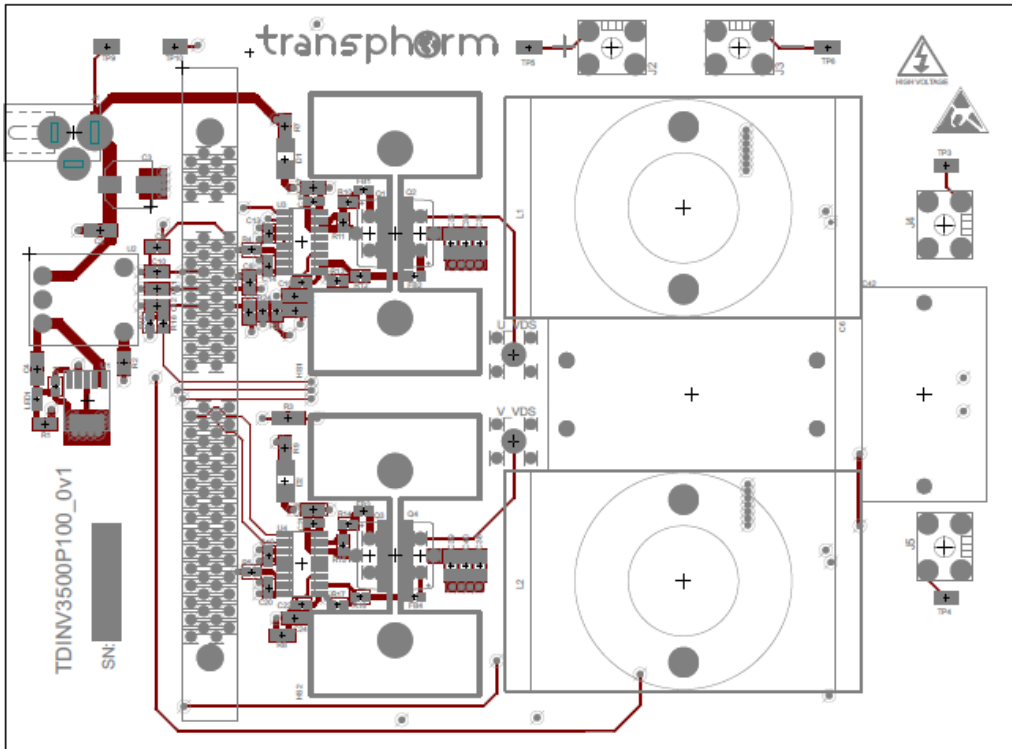
(a) PCB top layer
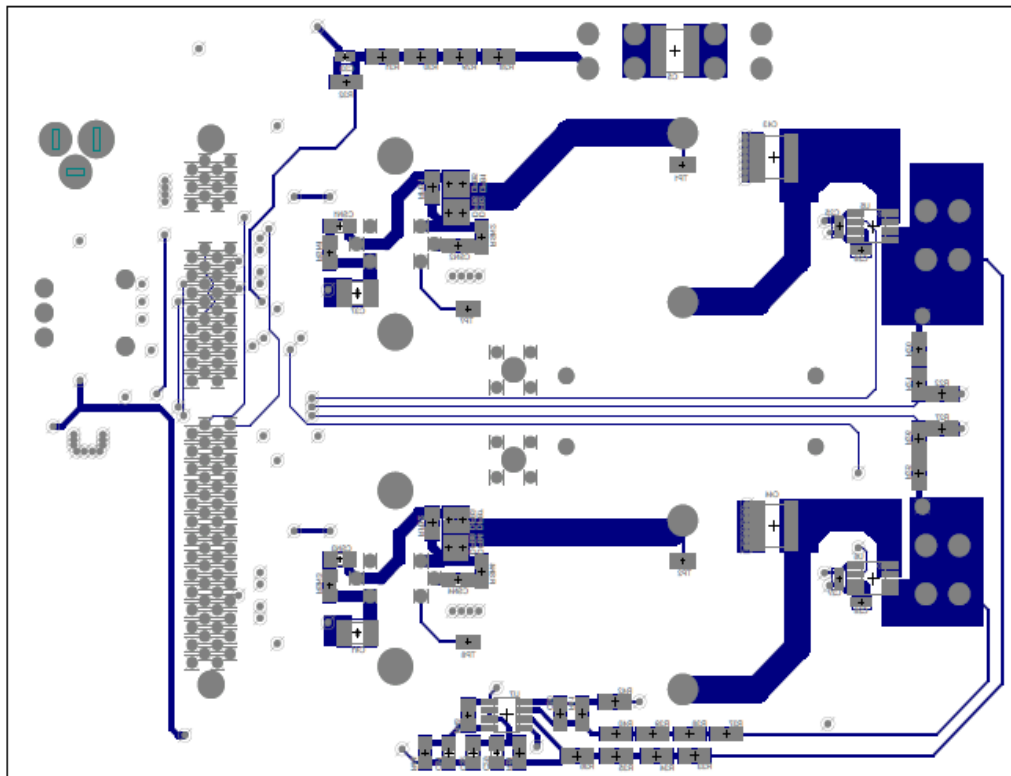
(b) PCB bottom layer

(c) PCB inner layer 2 (ground planes) and inner layer 3 (power plane)

Figure 9. PCB layers

Probing

There are two available Tektronix test points on the PCB used to monitor the low-side switching (node) capability of each half-bridge circuit during operation.

The board has eight other test point locations for probing: V_{CC}, V_{DD}, SN1, SN2, GS1, GS2, GND, GND.

To minimize inductance during measurement, the tip and the ground of the probe should be directly attached to the sensing points to minimize the sensing loop. For safe, reliable, and accurate measurement, a scope probe tip may be directly soldered to the low-side FET drain and a short ground wire soldered to the low-side FET source. See Figure 10 for an alternative that does not require soldering the probe tip.
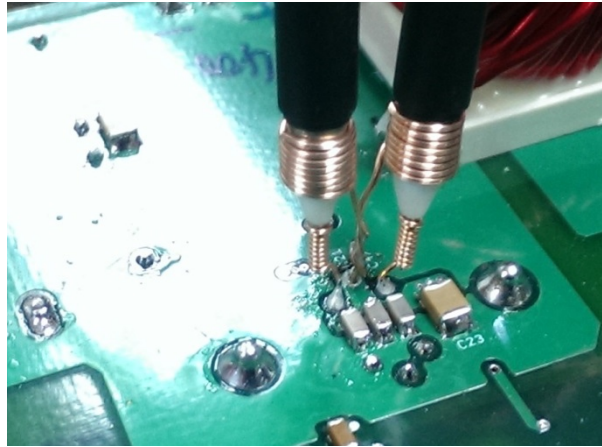
Figure 10. Low-inductance probing of fast, high-voltage signals

Protection features

Under-voltage lockout

The TDINV3500P100 evaluation board supports an under-voltage lockout feature. Be sure the feature is enabled if used. The board will blink red (LED LD2) on the control card in the event the board is in under-voltage and the output will be held off. When the under-voltage threshold is crossed, the output will be on and LED LD2 will be steady. The hysteresis value applies to the under-voltage trip threshold.

```
10 #define UNDER_VOLTAGE_ENABLE    0         // set to 1 to enable the under voltage lock out feature
11 #define UNDER_VOLTAGE_TRIP      20        // set the minimum voltage to begin operation
12 #define HYSTERESIS_SET          5         // set the amount of hysteresis for the under voltage function
13 #define OVER_VOLTAGE_TRIP       750       // set the over voltage limit here
```

Over-voltage shutdown

The over-voltage feature is always enabled so be sure the overvoltage trip level is set high enough. In this example, the over-voltage threshold is 750V. In the event of an over-voltage event both red LEDs on the control card will blink in unison. The board must be powered down to recover from this type of event.

```
11 #define UNDER_VOLTAGE_TRIP      20        // set the minimum voltage to begin operation
12 #define HYSTERESIS_SET          5         // set the amount of hysteresis for the under voltage function
13 #define OVER_VOLTAGE_TRIP       750       // set the over voltage limit here
```

Current limit shutdown

The TDINV3500P100 evaluation board supports user-defined current limit thresholds in both the positive- and negative-going directions. The current limits are peak and in amps. In this example limits are set at 6.3A in both the positive- and negative-going directions. In most cases these trip points would be set to the same value. In an over-current event both red LEDs on the control card will blink in unison. The board must be powered down to recover from this type of event.

```
14
15 #define COMPARATOR_MAX          9         // set the DAC value for the high side trip in amps
16 #define COMPARATOR_MIN          9         // set the DAC value for the low side trip in amps
17
```