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TDINV1000P100: 1kW Inverter Evaluation Board

Introduction

The TDINV1000P100 1kW inverter kit from Transphorm provides an easy way to evaluate the performance advantages of GaN power transistors in various inverter applications, such as solar and 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 150mΩ 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.

The TDINV1000P100-KIT is for evaluation purposes only.

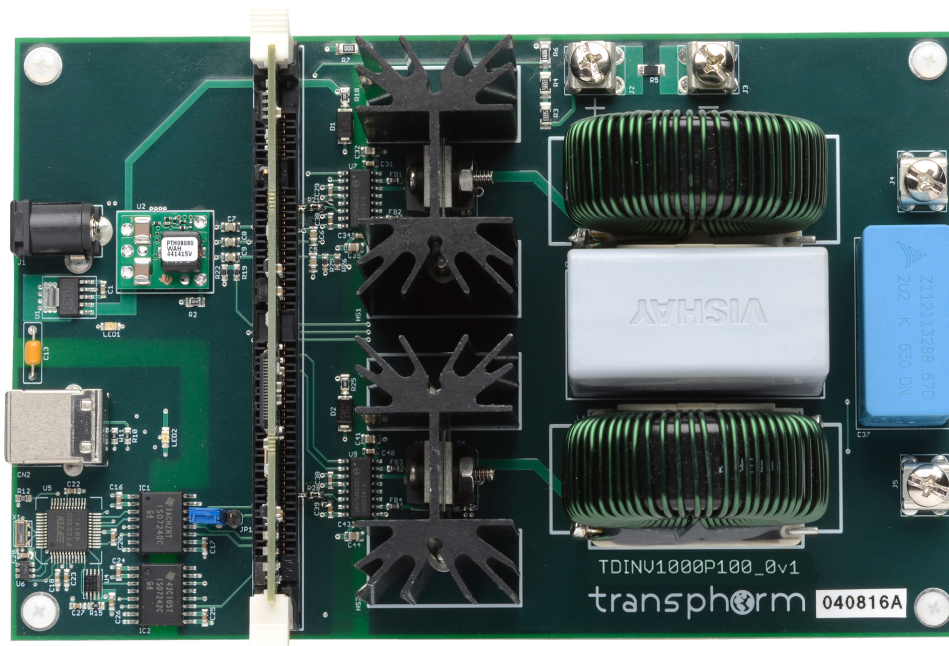


Figure 1. TDINV1000P100 inverter evaluation board

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 also available at transphormusa.com/pv1fw. 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 TDINV1000P100 circuit board is provided at the end of this user guide document, as well in the design files at transphormusa.com/pv1kit.

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The TDINV1000P100-KIT includes:

- TDINV1000P100 single phase inverter assembly
- Texas Instrument F28035 control card
- 9V power supply

TDINV1000P100 input/output specifications

High-voltage input: 400V_{DC} max

Auxiliary supply (J1): 9V_{CC}

Input: 0V_{DC} - 400V_{DC}

Output: $V_{DC} / \sqrt{2} V_{RMS}$ at 50/60Hz ¹, up to 1000VA

PWM frequency: 100kHz - 300kHz ²

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

Power dissipation in the GaN FET is limited by the maximum junction temperature. Refer to the [TPH3206PSB datasheet](#).

Circuit description

Refer to Figure 2 for a block diagram of the inverter circuit. A detailed schematic is also available in the design files at transphormusa.com/pv1kit.

The TDINV1000P100 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 9V input.

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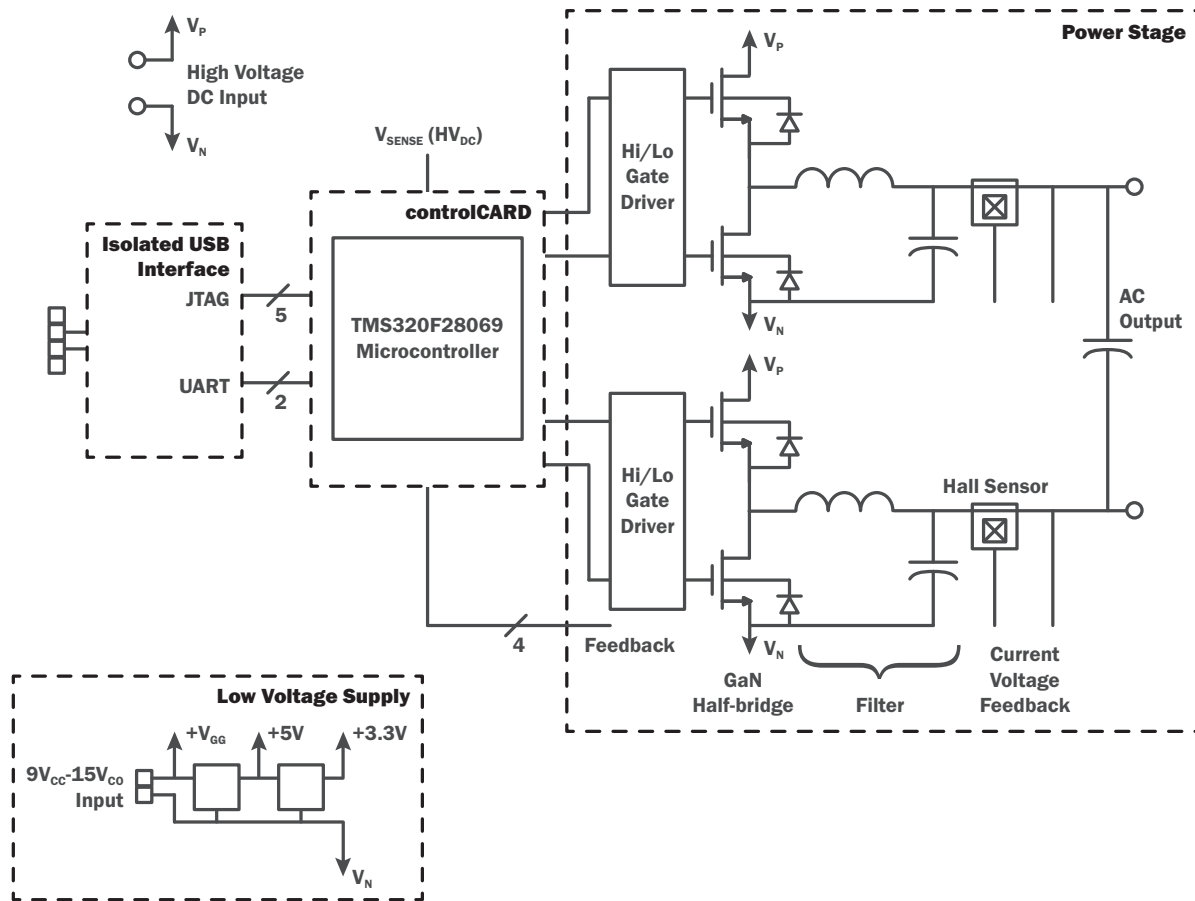


Figure 2. Circuit block diagram

The inverter takes advantage of diode-free operation, in which the freewheeling current is carried by the GaN FETs themselves, without the need of additional freewheeling diodes. For minimum conduction loss, the gates of the transistors 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.

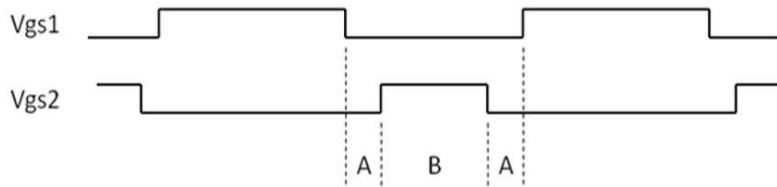


Figure 3. Non-overlapping gate-drive pulse; A is a deadtime set in the firmware

Gate drivers

High-voltage integrated drivers supply the gate-drive signals for the high and low-side power transistors. These are 2500V isolation drivers (Silicon Labs Si827x family), specifically chosen for high-speed operation without automatic deadtime insertion. The deadtime between turn-off of one transistor in a half bridge and turn-on of its mate is set in the firmware.

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Output filter

A simple LCL filter on the output (L3, L4, C37 and C54 - C57) 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 5 - 10kHz to accommodate 100kHz 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 U8 and U10 provide linear current feedback to the microcontroller. These signals could be used to control output power flow, and/or to protect against short circuits. The firmware provided with the kit, however, does not actually make use of this feedback. Note that these are placed at an intermediate point of the output filter. Refer to the bill of materials to confirm the sensor part numbers, but typical would be the Allegro ACS712-20A sensor, which has a $\pm 20A$ range (100mV/A). These parts are pin compatible with a $\pm 5A$ and $\pm 30A$ versions of ACS712, 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 standard USB cable. The isolated USB interface enables simultaneous operation of two physical ports to the microcontroller: a JTAG port for debug and loading of firmware, and a UART for communication with a host application.

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.

Heat sink

The two TO-220 GaN transistors on each half-bridge are mounted on a common heat sink. The heatsink is adequate for 1000W operation WITHOUT forced air flow. Even higher efficiency at high power may be achieved by minimizing the temperature rise. This may be accomplished with forced 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 400V_{DC}. A 22 μ F, low ESR, film capacitor is provided as a bypass capacitor for the high voltage supply, along with several smaller value ceramic capacitors in parallel. This is not intended to provide significant energy storage, but to provide high frequency bypassing. 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 9V input (V_{GG}). A wall-plug adaptor is provided.

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Note that only the USB port is isolated; all other 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.

Connection sequence

Refer to Figure 4. Insert the microcontroller card to the DIM100 socket before applying any power to the board. To use the preloaded firmware, verify that jumper JP1 is removed. This releases the JTAG port and allows the microcontroller to boot from flash. For communication with a host over the JTAG port, JP1 should be installed.

With the supply turned off, 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_{GG} (9V) 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 (CN3). LED2 should illuminate, indicating isolated +5V power is applied over the USB cable.

Turn on the high voltage power. The high-voltage supply may be switched ON instantly or raised gradually.

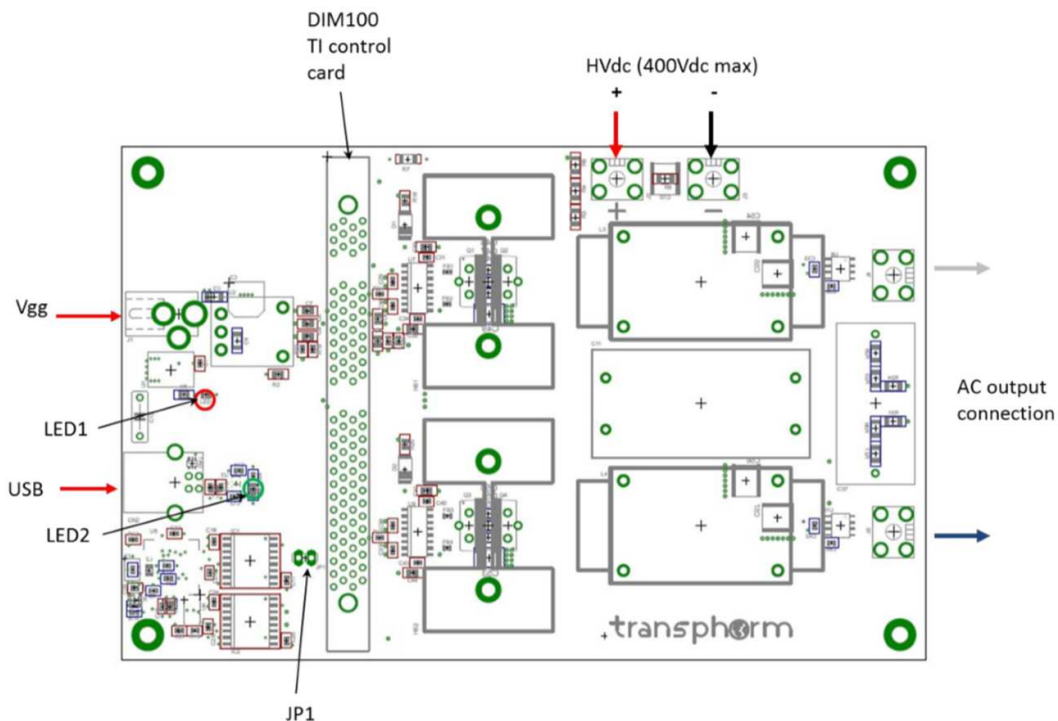


Figure 4. Connections

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Test

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.

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 350V_{DC} source and output power to a resistive load were measured with a Yokogawa WT1800 power analyzer.

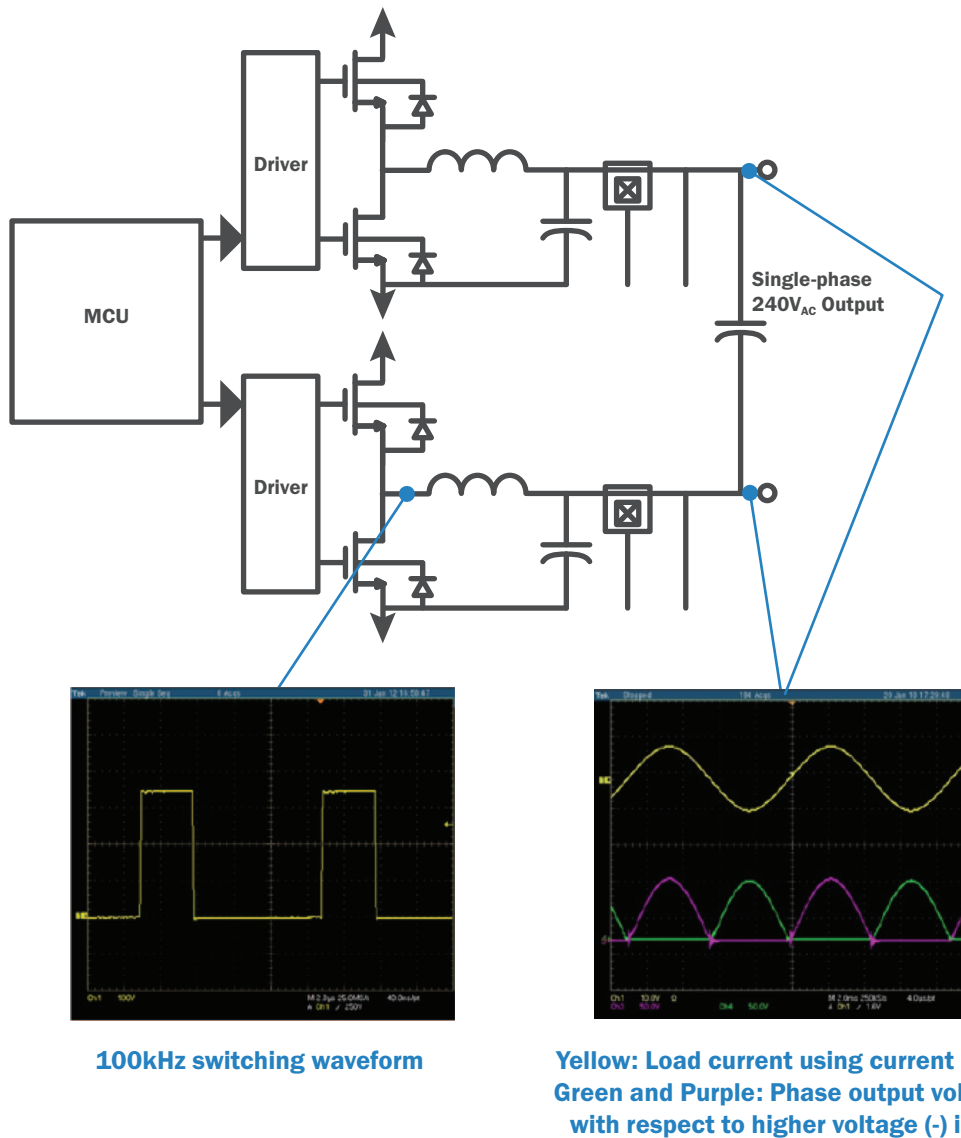


Figure 5. Typical waveforms

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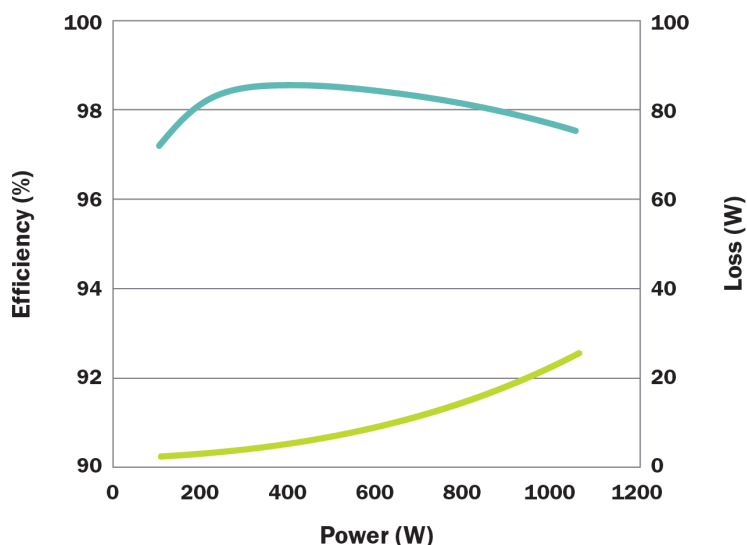


Figure 6. Typical efficiency: 350V_{DC} input, 240V_{AC} output

Design details

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

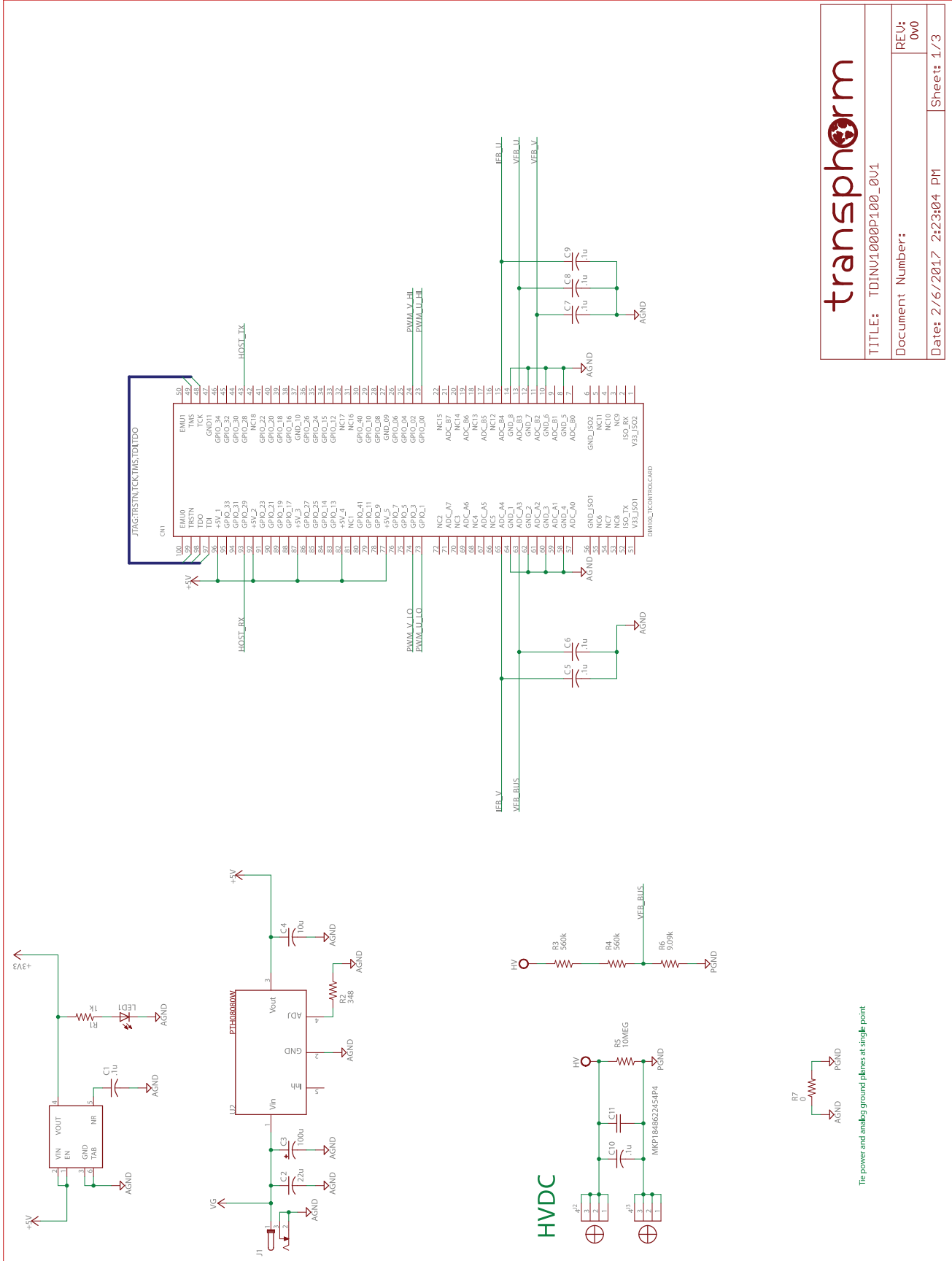
Table 1. TDINV1000P100 evaluation board bill of materials (BOM)

Designator	Qty	Value	Description	Part Number	Manufacturer
X1	1		CSTCR	CSTCR6M00G53Z-R0	Murata
HS1, HS2	2		529802B02500G	529802B02500G	Murata
D1, D2	2		DO-214AC	ES1J	Aavid Thermalloy
FB1, FB2, FB3, FB4	4	120Ω ferrite bead	603	MMZ1608Q121B	Fairchild
LED1, LED2	2		CHIP-LED0805	SML-211UTT86	TDK
C49, C53	2	0.1μF	C1812	C1812V104KDRACTU	ROHM
C1, C14, C16, C17, C19, C20, C21, C22, C23, C24, C25, C26, C27, C28, C29, C30, C31, C33, C34, C38, C39, C40, C42, C43	24	0.1μF	C0603	06033C104JAT2A	Kemet
C5, C6, C7, C8, C9	5	0.1μF	C0805	08053C104KAT2A	AVX
C10, C54, C55, C56, C57	5	0.1μF	C2225K	VJ2225Y104KXGAT	AVX
R21, R28	2	DNI	R0603	DNI	Vishay
R7	1	0Ω	R1206	ERJ-8GEY0R00V	Panasonic
R14	1	1MΩ	R0603	ERJ-3EKF1004V	Panasonic
R8, R15	2	1kΩ	R0603	CRCW06031K00FKEA	Vishay
R1	1	1kΩ	R0805	ERJ-6GEYJ102V	Panasonic
C36, C45	2	1nF	C0603	DNI	AVX
C12, C18	2	1μF	C0603	CC0603KRX5R6BB105	Yageo
C15	1	2.2μF	C0603	0603YD225MAT2A	AVX
R13, R17	2	2.2kΩ	R0603	ERJ-3GEYJ222V	Panasonic
C46, C47, C48, C50, C51, C52	6	4.7nF	C1206	C1206C472KDRACTU	Kemet
R19, R26	2	5.23kΩ	R0603	ERJ-3EKF5231V	Panasonic
R6, R24, R31	3	9.09kΩ	R1206	ERJ-8ENF9091V	Panasonic
R18, R25	2	10Ω	R0805	ERJ-6GEYJ100V	Panasonic

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Designator	Qty	Value	Description	Part Number	Manufacturer
R22, R29	2	10.2kΩ	R0603	ERJ-3EKF1022V	Panasonic
R5	1	10MΩ	R1206	HVCB1206FKC10M0	Stackpole
R12, R16	2	10kΩ	R0603	ERJ-3GEYJ103V	Panasonic
C32, C35, C41, C44	4	10μF	C0805	C0805C106M4PACTU	Kemet
C4	1	10μF	C1206	CL31A106KAHNNNE	AVX
C2	1	22μF	C1206	CL31X226KAHN3NE	Samsung Electronics
L1, L2	2	22μH	805	LQM21FN220N00L	Murata
R10, R11	2	27Ω	R0603	CRCW060327ROFKEA	Vishay
U6	1	93LC46B	SOT23-6	93LC46BT-I/OT	Microchip
R2	1	348Ω	R0805	ERJ-6ENF3480V	Panasonic
R9	1	470Ω	R0603	ESR03EZPF4700	ROHM
R3, R4, R20, R23, R27, R30	6	560kΩ	R1206	RC1206FR-07560KL	Yageo
U8, U10	2	ACS712	S08	ACS712ELCTR-20A-T	Allegro Microsystems
DA1	1	BAW567	SOT363	BAW567DW-7-F	Diodes Inc
U5	1	FT2232D	LQFP48	FT2232D-REEL	FTDI
IC1	1	IS07240	SO-16DW	IS07240CDW	Texas Instruments
IC2	1	IS07242	SO-16DW	IS07242CDW	Texas Instruments
U4	1	LVC2G74	DCT	SN74LVC2G74DCTR	Texas Instruments
U7, U9	2	SI8273AB1	SOIC16N	SI8273AB1	Silicon Labs
U3	1	TPS73033	SOT23-5	TPS73033DBVR	Texas Instruments
U1	1	TPS79533	SOT223-6	TPS79533DCQR	Texas Instruments
J2, J3, J4, J5	4		KEYSTONE_7691	7691	Keystone
	2	Q1, Q3 insulator		SP2000-0.015-00-54	Bergquist
	2	Q2, Q4 insulator		53-77-9G	Aavid Thermalloy
C11	1	MKP1848622454P4	MKP1848622454P4	MKP1848622454P4	Vishay
U2	1	PTH08080WAH	PTH08080W_TH	PTH08080WAH	Texas Instruments
C13	1	100nF	C075-032X103	SA111E104MAR	AVX
C37	1	2μF/630V	EPCOS_B32674	B32674D6225K	Epcos
JP1	1		1X02	961102-6404-AR	3M
J1	1		PJ-002AH	PJ-002AH	CUI Inc
CN2	1		USBSHIELD	897-43-004-90-000000	Mill-Max
C3	1	100μF	PANASONICSMALCAP6X6	EEE-FPE101XAP	Panasonic
plastic shoulder washers	4	plastic shoulder washers	plastic shoulder washers	3049	Keystone
CONN SHUNT 2POS .100	2	jumper	CONN SHUNT 2POS .100	65474-002LF	FCI
#4-40, 3/8" Phillips pan head screw	2	#4-40, 3/8" Phillips pan head screw	#4-40, 3/8" Phillips pan head screw	9901	Keystone
#4-40 hex nut	1	#4-40 hex nut	#4-40 hex nut	4694	Keystone
standoffs 4-40 5/8"	4	standoffs 4-40 5/8"	standoffs 4-40 5/8"	1902F	Keystone
Q1, Q2, Q3, Q4	4	TPH3206PSB	TPH3206PSB	TPH3206PSB	Transphorm
	1	Control card Piccolo F28035	Control card Piccolo F28035	TMDSCNCD28035	Texas Instruments
L3, L4	2	295μH inductor	295μH inductor	CWS-1SN-12471	CWS
CN1		Control card connector	control card connector	TMDSDIM100CON5PK	Texas Instruments
	1	9V adaptor	Accessory	CUI	CUI
	4	Nylon screw for standoffs	nylon screw for standoffs	9330	Keystone

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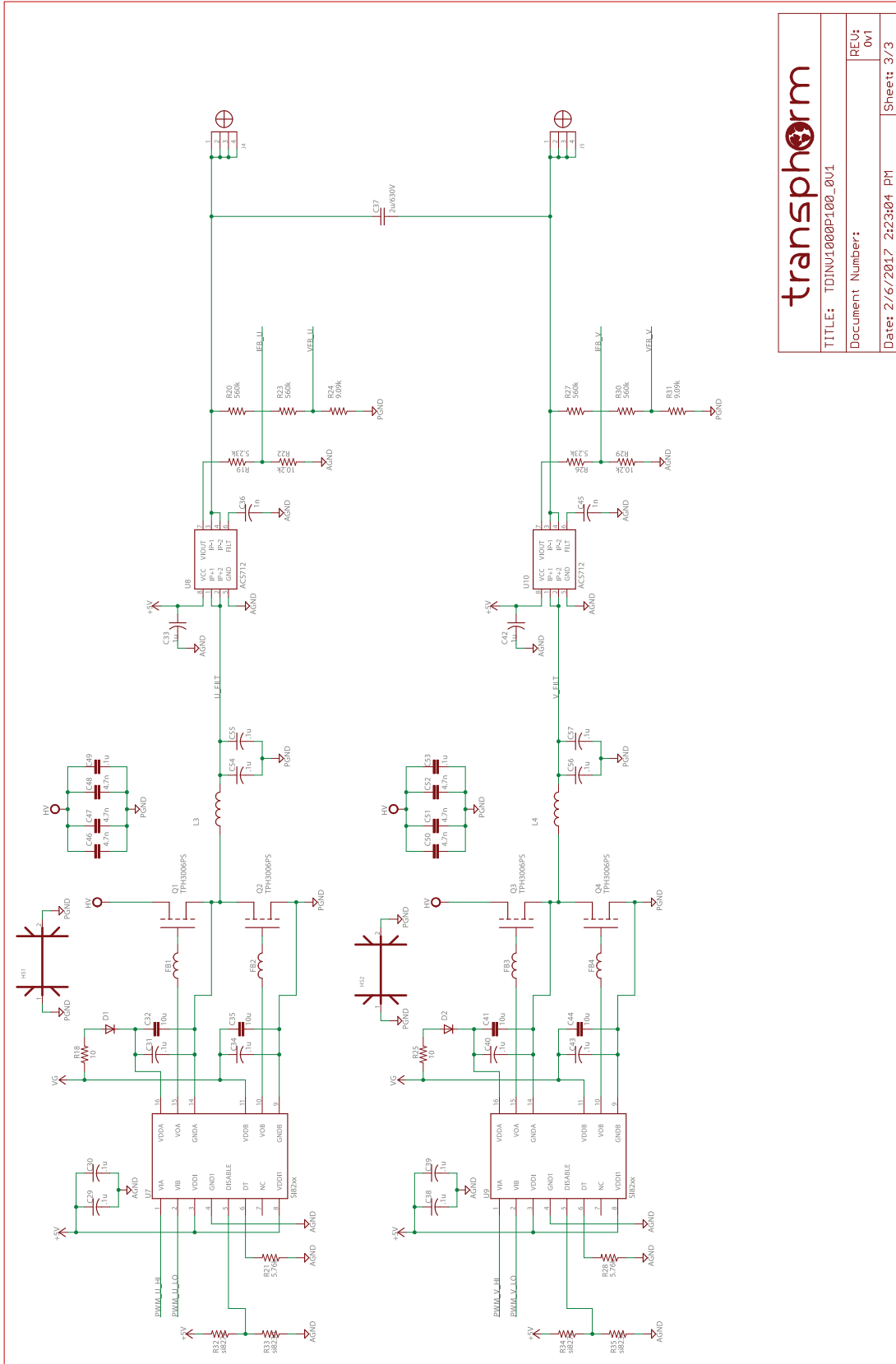
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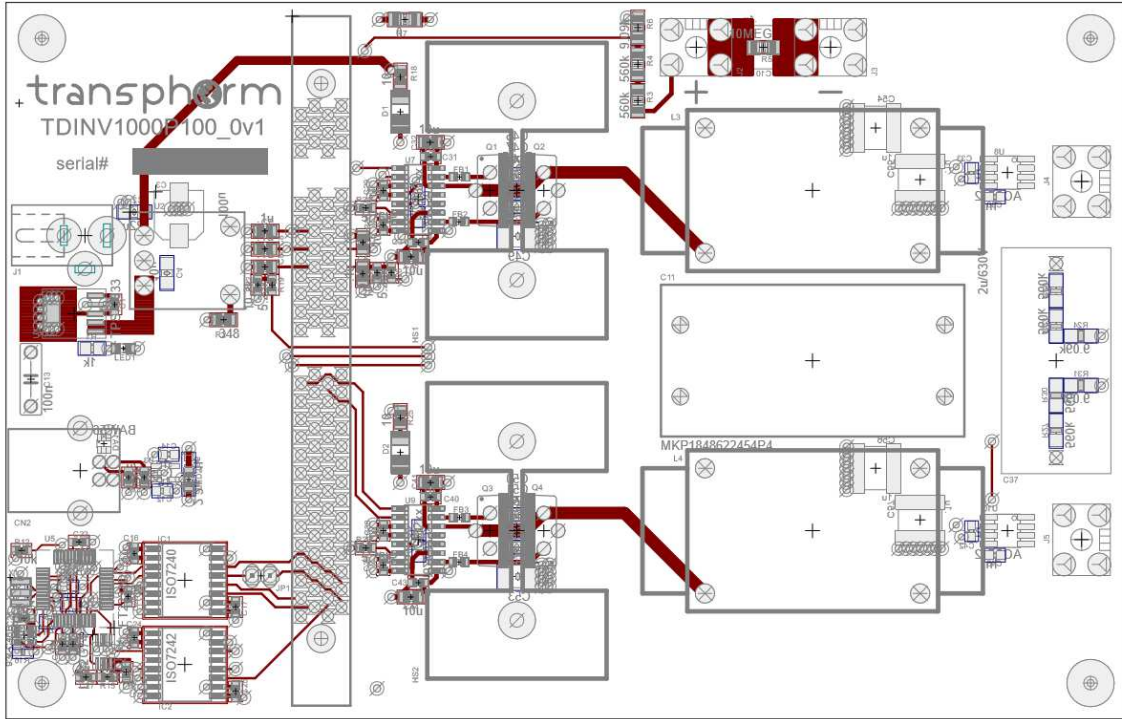
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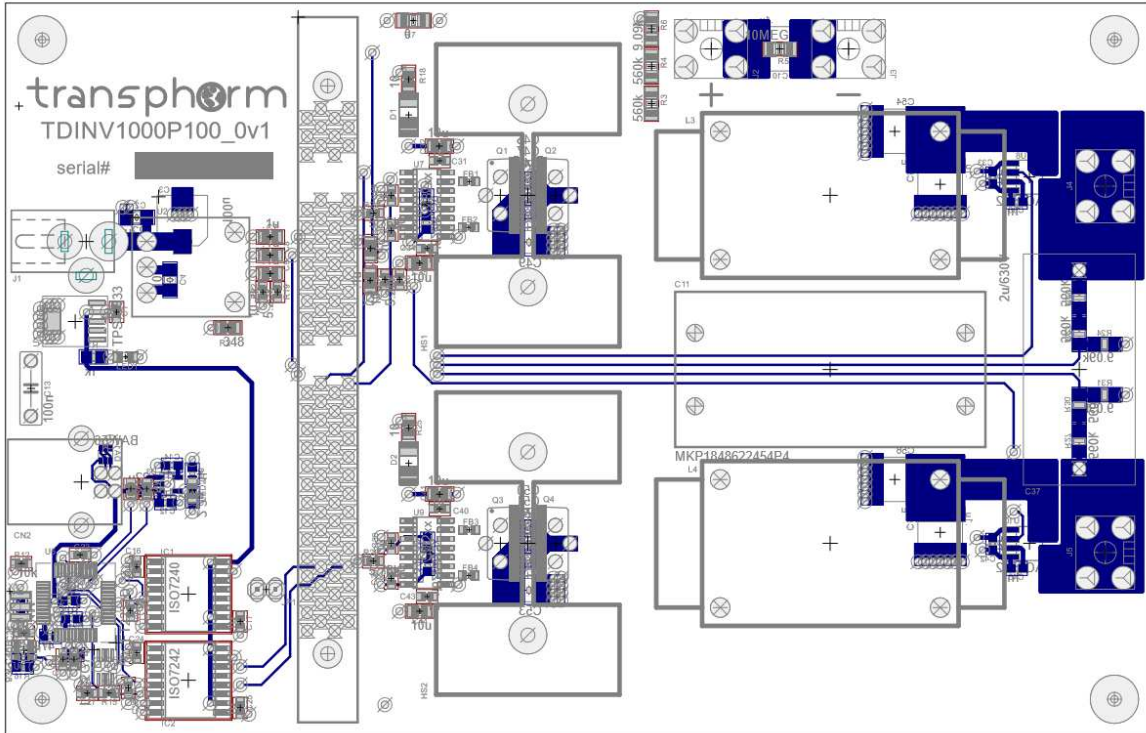
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Figure 7. Detailed circuit schematics

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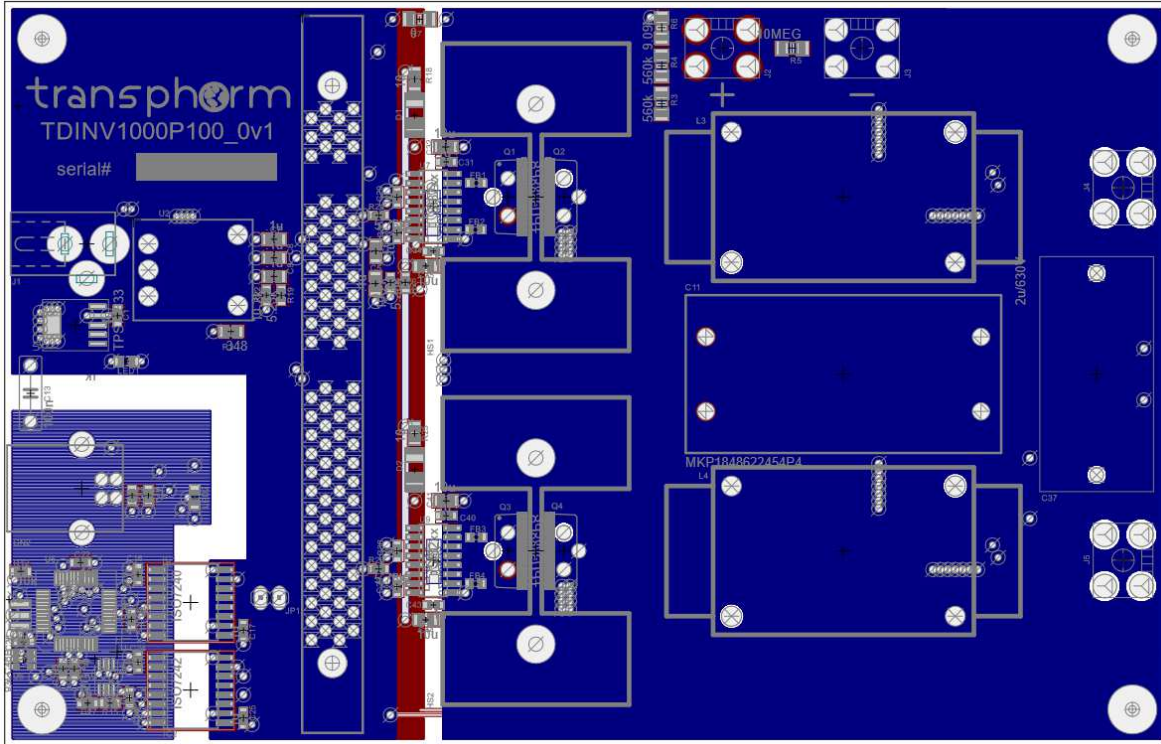


(a) PCB top layer



(b) PCB bottom layer

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

Figure 8. PCB layers

Probing

There are no test points provided for probing the low-side gate or half-bridge switching node. 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 9 for an alternative that does not require soldering the probe tip.

Warnings

There is no specific protection against over-current or over-voltage on this board. The TDINV1000P100 board is for evaluation purposes only.

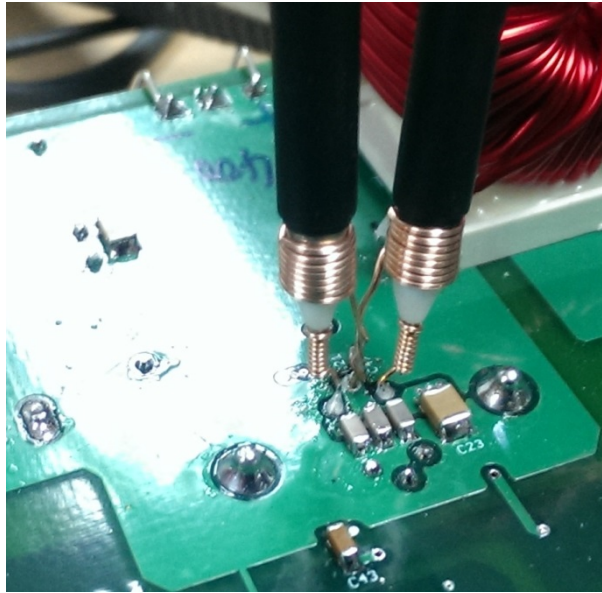


Figure 9. Low-inductance probing of fast, high-voltage signals