

TI Designs: TIDA-00951

2-kW, 48- to 400-V, >93% Efficiency, Isolated Bidirectional DC-DC Converter Reference Design for UPS



1 Description

The TIDA-00951 design provides a reference solution for a 2-kW isolated bidirectional DC-DC converter capable of power transfer between a 400-V DC bus and a 12- to 14-cell Lithium battery pack for use in UPS, battery backup and power storage applications.

This TI Design works as a >93% efficient, current fed, active clamped boost converter with ZVS in the backup mode and voltage fed full-bridge batter charger with >93% efficiency in the charging mode. This TI Design has built-in protection for DC bus overcurrent and overvoltage and battery overcurrent.

2 Resources

TIDA-00951	Design Folder
SN6505B	Product Folder
CSD19536KCS	Product Folder
UCC27211A	Product Folder
UCC27517A	Product Folder
AMC1301	Product Folder
TMP300	Product Folder
LM4041A12	Product Folder
TPS62160	Product Folder
TLV1117	Product Folder
OPA376	Product Folder
TIDA-01281	Design Folder
TIDA-01141	Design Folder
TIDA-01159	Design Folder

3 Features

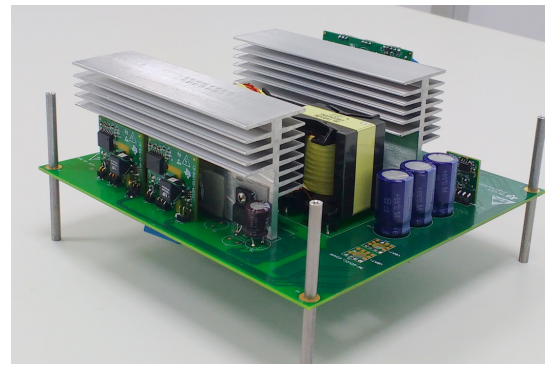
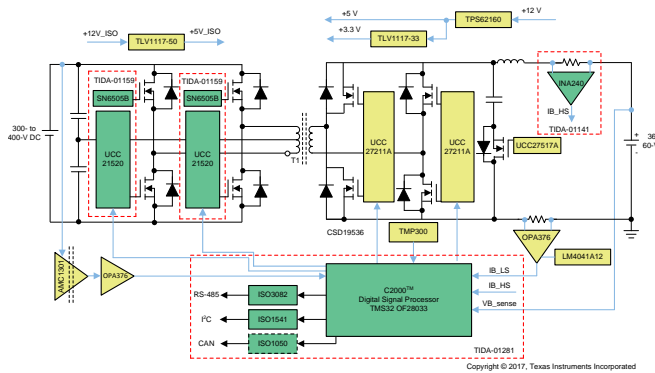
- Digitally Controlled Isolated Bidirectional DC-DC Converter
- Operates as Active Clamped Full Bridge Boost Converter With ZVS For All Low-Voltage Switches at High Loads
- Operates as Active Clamped Voltage Fed Buck Converter With Synchronous Rectification to Improve Efficiency When Charging Battery
- Wide Operating Range From 36- to 60-V Battery and 300- to 400-V DC Bus
- Cost Optimized Design Using 100-V FET on Low-Voltage Side, Eliminates Requirement for Paralleling Multiple FETs up to 2 kW
- Built-in Cold Start Procedure and Fast Mode Transfer (< 100 μ S) From Battery Charger to Backup Power Supply
- Onboard Isolated Communication Interface for CAN, I²C, and RS-485

4 Applications

- Server PSUs and Telecom Rectifiers
- Uninterruptible Power Supplies (UPS)
- Industrial Power Supplies
- Battery Chargers
- Energy Storage Systems



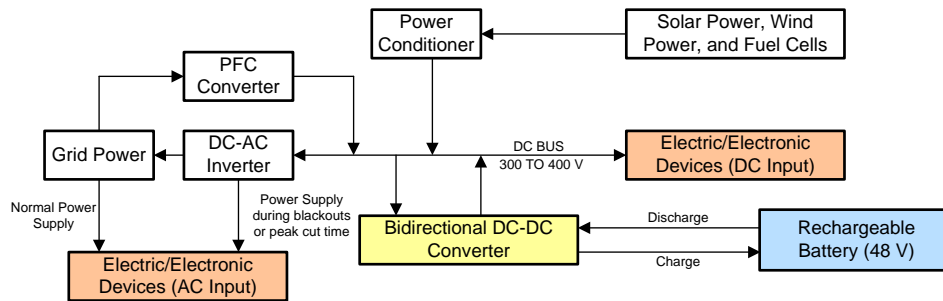
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5 System Description

Most backup power equipment such as DC inverters, home inverters, industrial DC-UPS, and energy storage banks require an exchange of power from the battery to the load and vice versa. Typical power-system distribution architecture with battery backup is shown in Figure 1:



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Figure 1. Top-Level Architecture of Typical UPS System

During normal operation, the main DC bus is regulated between 300 and 400 V through the grid source of a building, factory, or house. Alternatively, the DC bus can be powered through a renewable energy source such as solar power generation or wind power generation, which is conditioned through a power conditioner to feed the DC bus. The battery acts as an energy storage unit, and it can be charged either through the grid or an external renewable energy source.

Conventionally, charging a battery through a DC bus and discharging the battery during power blackouts are implemented with two unidirectional converters, each processing the power in one direction. With a growing emphasis on compact and efficient power systems, there is increasing interest in using bidirectional converters, especially in DC inverters, home inverters, and energy storage banks. A bidirectional DC-DC converter, capable of bilateral power flow, provides the functionality of two unidirectional converters in a single converter unit.

The TIDA-00951 design is an isolated bidirectional DC-DC converter designed to exchange the power between a 300- to 400-V DC Bus and 48-V battery banks. The design has a full-bridge power stage on the high-voltage (HV) side, which is isolated from a current-fed full-bridge stage on the low-voltage (LV) side. During the presence of the DC bus (normal conditions), the design operates in buck mode and charges the battery with constant current until the battery voltage is in regulated limits. During blackouts, the design operates as the current-fed full-bridge converter to boost the power from a 48-V battery (36- to 60-V input) to the 380-V DC bus and supports the load with backup.

The transition or change over time from the charge to backup mode is very critical for ensuring continuity of power to the loads. The TIDA-00951 has transition time of less than 100 μ s, which reduces the amount of bulk capacitance needed for the system to provide power during the transition time.

This TI Design operates at peak efficiency of 93% in buck mode (as charger) and 94% in boost mode (during discharge). The high discharge efficiency provides a high run time from the battery. Operating at a high switching frequency of 100 kHz, the design has a compact form factor of 185 mm \times 170 mm for the power level of 2 kW.

The TIDA-00951 design is optimized for component count, cost, and performance. Various parameters of the design like regulation, efficiency, output ripple, transition time, startup, and switching stress across the devices were tested and documented in the following sections.

5.1 Key System Specifications

Table 1. Key System Specifications

PARAMETER	TEST CONDITIONS	MIN	NOM	MAX	UNIT
BACKUP SUPPLY MODE					
INPUT CONDITIONS					
Input battery voltage (V_{BAT})	—	36	44.4	60	V
Input battery current (I_{BAT_MAX})	—	—	—	60	A
OUTPUT CONDITIONS					
Output bus voltage (V_{BUS})	—	300	380.0	400	V
Output bus current (I_{BUS_MAX})	$V_{BAT} > 40\text{ V}$	—	—	5	A
Line regulation		—	—	1	%
Load regulation		10% to 100% load	—	—	1
Output voltage ripple	—	—	—	—	—
Input voltage ripple	—	—	—	—	—
Average efficiency	20% to 100%	—	—	—	%
Full load efficiency	—	—	—	—	%
BATTERY CHARGER					
INPUT CONDITIONS					
Input bus voltage (V_{BUS})	—	300	380.0	400	V
Input bus current (I_{BUS_MAX})	—	—	—	60	A
OUTPUT CONDITIONS					
Output battery voltage (V_{BAT})	—	36	44.4	60	V
Output battery current (I_{BAT})	—	—	—	16	A
SYSTEM SPECIFICATIONS					
Operating ambient	—	-10	25	55	°C
Board size	Length x Width x Height	185 x 173 x 8			mm

6 System Overview

6.1 Block Diagram

Figure 2 shows the high-level block diagram of the TIDA-00951. The DC-DC converter is made of a current-fed full-bridge converter on the battery side and a full-bridge on the 380-V bus side. The control of the system is through the C2000™ present on the TIDA-01281 control card. The TIDA-01159 isolated gate driver card is used to drive the full bridge on the 380-V bus side. High-side inductor current sensing is performed using the TIDA-01141 board.

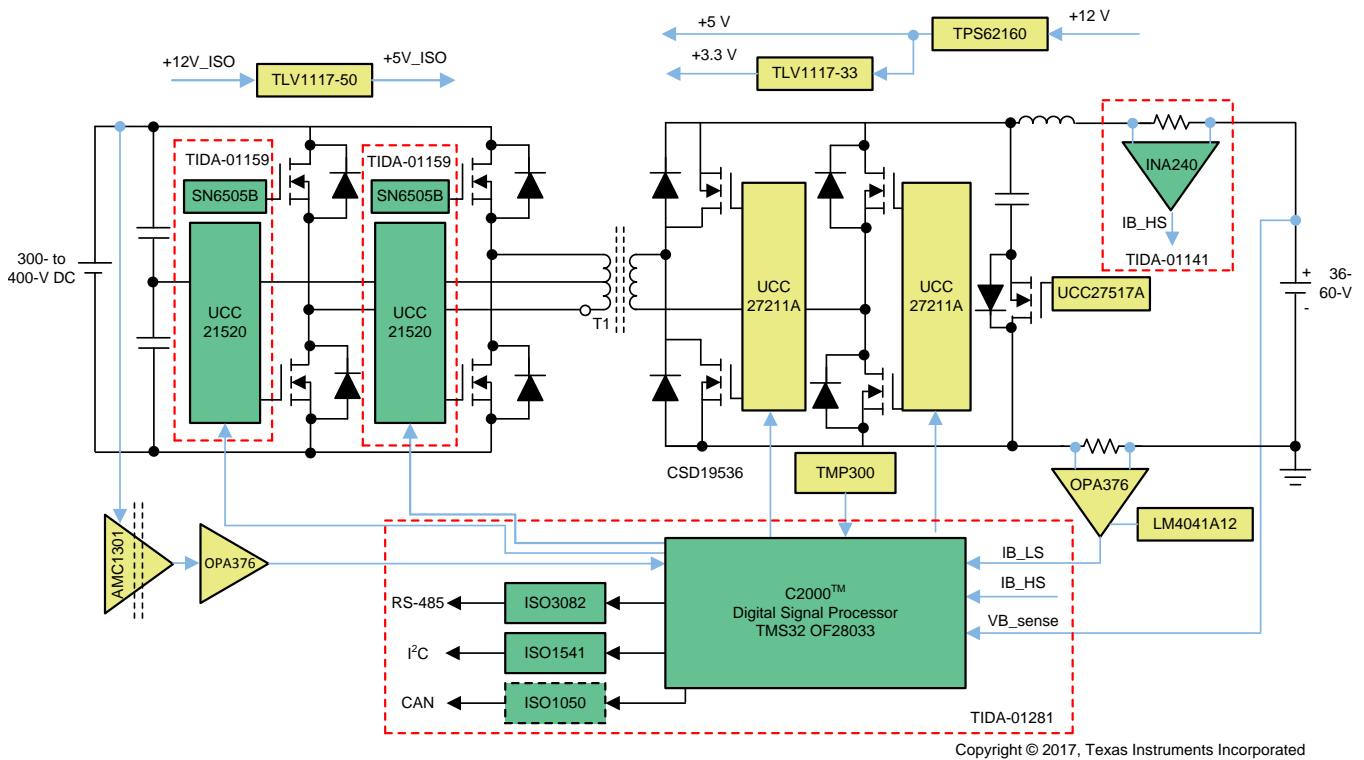


Figure 2. Block Diagram of 2-kW Isolated Bidirectional DC-DC Converter

6.2 Highlighted Products

This TIDA-0951 reference design features the following devices, which were selected based on their specifications. The key features of the highlighted products are mentioned in the following subsections. For more information on each of these devices, see their respective product folders at <http://www.ti.com> or click on the links for the product folders in the Section 2 section.

6.2.1 CSD19536KCS

The CSD19536KCS is a 100-V NexFET™ MOSFET has a very low $R_{DS(on)}$ of 2.3 mΩ with an ultra-low Q_g and Q_{gd} of 118 nC and 17 nC, respectively. In the TIDA-00951 design, five of these MOSFETs are used on the battery side or LV side to form the LV full bridge and the active clamp circuit. Because the LV FET is turned on at ZVS at high loads, the $R_{DS(on)}$ parameter becomes important in determining the loss on the FET. The CSD19536KCS was chosen for its very low $R_{DS(on)}$.

6.2.2 UCC27211A

The UCC27211A is a robust 120-V half-bridge gate driver capable of delivering up to a 4-A source and sink current for driving power MOSFETs. With very low pullup and pulldown resistances, this device reduces the transition time of the power MOSFET through the Miller region, which minimizes the switching loss on the MOSFET. The device is a robust half-bridge gate drive with input pins capable of tolerating up to a -10-V input voltage. This TI Design takes advantage of this device's ability to minimize the switching loss on the power MOSFET on the LV side at turnoff to operate at a high switching frequency of 100 kHz per phase. Find more details on this driver from the device datasheet ([SLUSBL4](#)).

6.2.3 SN6505B

The SN6505B is a low-noise, low-EMI push-pull transformer driver, specifically designed for small form factor, isolated power supplies. It drives low-profile, center-tapped transformers from a 2.25- to 5-V DC power supply. Ultra-low noise and EMI are achieved by slew rate control of the output switch voltage and through spread spectrum clocking (SSC). The SN6505 consists of an oscillator followed by a gate drive circuit that provides the complementary output signals to drive ground referenced N-channel power switches. The device includes two 1-A Power-MOSFET switches to ensure start-up under heavy loads. The switching clock can also be provided externally for accurate placement of switcher harmonics or when operating with multiple transformer drivers. The internal protection features include a 1.7-A current limiting, undervoltage lockout, thermal shutdown, and break-before-make circuitry. The SN6505B includes a soft-start feature that prevents high inrush current during power up with large load capacitors.

6.2.4 OPA376

The OP376 family of low-noise operational amplifiers (op amp) with e-trim offers outstanding DC precision and AC performance. The OPA376 is single op amp with rail-to-rail input and output, low offset (25 μV max), and an ability to operate with common-mode voltages up to 100 mV below the ground. Low noise (7.5 $\text{nV}/\sqrt{\text{Hz}}$), a quiescent current of 950 μA max, and a bandwidth of 5.5 MHz make this part a good fit for this TI Design.

For the TIDA-00951, the OPA376 is used for low-side bidirectional current sensing, where low offset voltage and high gain bandwidth product are important in minimizing the current sense resistor value.

6.2.5 LM4041-N

The LM4041-N is a precision voltage reference, which gives a fixed 1.2-V reference voltage. The LM4041-N device's advanced design eliminates the need for an external stabilizing capacitor while ensuring stability with any capacitive load, which makes the LM4041-N easy to use. Curvature correction in the band-gap reference temperature drift and low-dynamic impedance ensure stable reverse breakdown voltage accuracy over a wide range of operating temperatures and currents. The LM4041-N 1.2 is used to provide a precise reference offset voltage to the current sense amplification circuit (based on the OPA376) to enable bidirectional current sensing.

6.2.6 TIDA-01281

The TIDA-01281 is a TSM320F28033-based control and communications reference design. It acts as the control card for the TIDA-00951 design. The TMS320F28033 present on-board samples the various voltages and currents on the TIDA-00951 board and generates the control signals and PWM required for proper functioning of the TIDA-00951 design. Apart from this the board also contains isolate communication interface ICs for implementing isolated I2C, CAN and RS485 communication.

6.2.7 TIDA-01141

The TIDA-01141 is a bidirectional high-side current sensing card based on the INA240 current sense amplifier. The INA240 is a voltage output current sense amplifier with an enhanced PWM rejection feature. Capable of operating with a common-mode voltage from -4 to 80 V with a DC CMRR of 132 dB, this device is well suited for high-side current measurement in SMPS and motor control applications.

6.2.8 TIDA-01159

The TIDA-01159 is an isolated half-bridge gate drive card based on the UCC21520 and SN6505B. It is used on the TIDA-00951 to drive the isolated HV-side full-bridge power stage.

6.3 System Design Theory

The isolated bidirectional DC-DC converter has two major modes of operation. When it is working as a backup power supply, it operates as an active clamped current-fed boost converter transferring power from the battery to the 380-V DC bus. When operating as a battery charger, the DC-DC converter works as a buck converter transferring power from the 380-V DC bus to the battery.

Apart from the two major modes, there is an additional mode for the cold starting the system. This mode is used to start up the TIDA-00951 in case the HV DC bus is completely discharged before board start-up.

The working of the isolated bidirectional DC-DC converter design is detailed in the following sections.

6.3.1 Boost Mode

6.3.1.1 Topology Description

When working in boost mode, the system needs to boost an input voltage between 36 to 60 V to a 380-V DC output. There are multiple topologies that can be considered for this TI Design.

Broadly speaking, the possible topologies can be classified into voltage- or current-fed topologies have an input inductor, which is connected to the power stage. However, a voltage-fed converter connects the input filter capacitor to the power stage. The presence of this input inductor gives the following benefits:

- Boosted voltage reduces the stress in the transformer and better utilization
- Avoids flux imbalance issues in the power stage
- Lower stress on the input filter capacitors due to reduction in the current ripple due to the input inductor

The TIDA-00951 works as an active clamped current-fed full-bridge converter in boost mode. Although there are several advantages in using a current-fed converter, one primary disadvantage is the huge spike in the current-fed converter at MOSFET turnoff. This turnoff requires some form of snubbing using either an active or passive snubber.

In the TIDA-00951 design, an active clamp comprising of a capacitor and a MOSFET has been used to implement an active snubber. The advantage of this active clamp is that not only does it recover the leakage energy, but it also helps in achieving ZVS for the primary LV MOSFET at turnon, thereby reducing the switching losses.

When working as a battery charger, the TIDA-00951 works as a voltage-fed buck converter. It transfers power from the HV DC bus and charges the battery in constant-current/constant-voltage (CC/CV) mode with a current limit of 16 A.

The following two sections explain how the converter in the backup supply mode works.

6.3.1.2 Boost Mode Working: Active Clamp

The power stage of the TIDA-00951 is shown in [Figure 3](#).

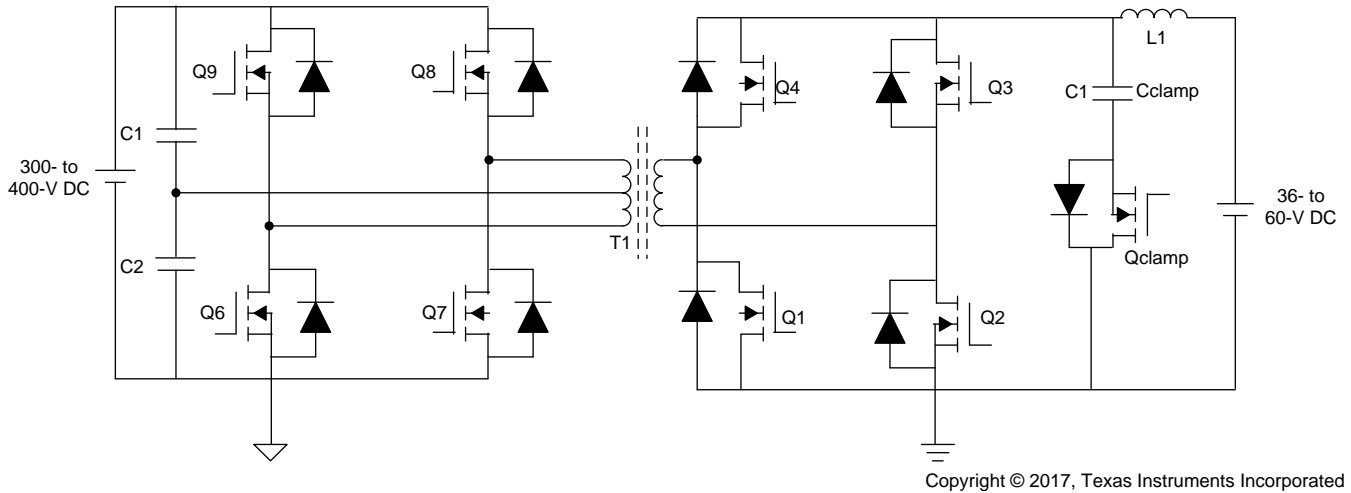
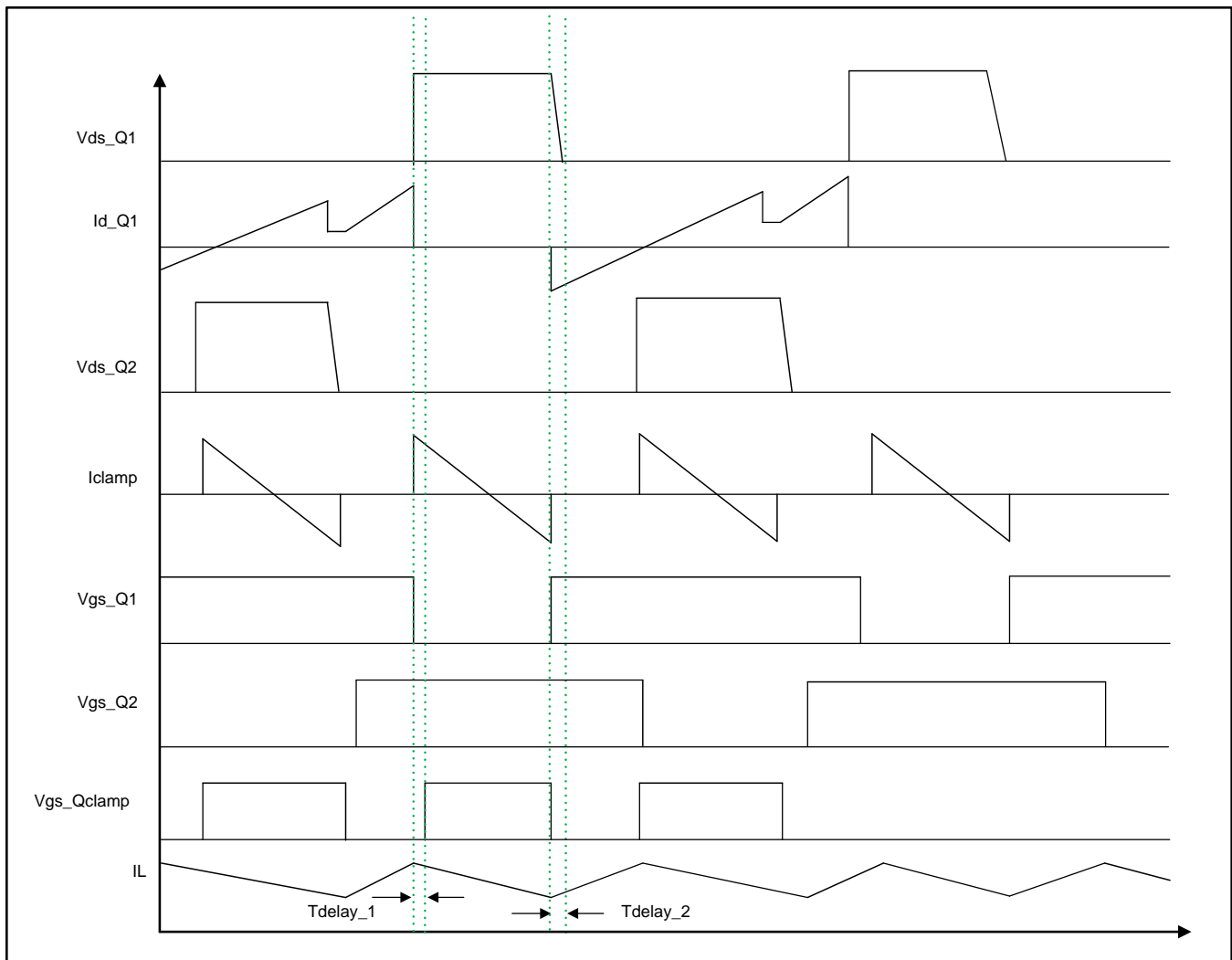


Figure 3. Power Stage of TIDA-00951

The switches Q1 to Q4 are the LV-side full-bridge MOSFET. The switches Q6 to Q9 form the HV-side full-bridge MOSFET. The capacitor C_{clamp} and switch Q_{clamp} form the active clamp.

When the system works as a current-fed full bridge, transferring power from the battery to the DC bus, the active clamp stores the additional leakage energy when the MOSFET Q1 to Q4 turnoff, thereby limiting the turnoff spike on the MOSFET. Additionally, by controlling the switching of the MOSFET Q5, the primary LV MOSFET can be turned on in or close to 0 V, thereby reducing the turnon switching losses.

The modality of implementing this scheme is shown in [Figure 4](#).



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Figure 4. Active Clamp Waveforms

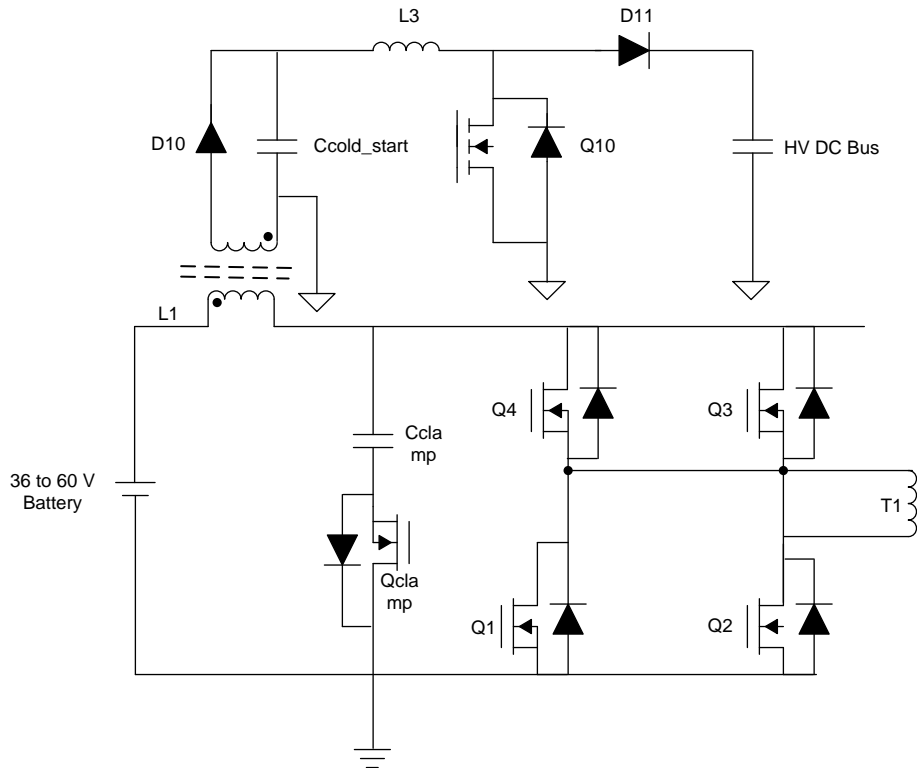
Take the switch pair Q1 and Q3 as an example to describe the working of the active clamp. When the switch pair Q1 to Q3 turn off, the current through FETs before turnoff get transferred and start flowing into the clamp capacitor and the body diode of Q_{clamp} . Because the clamp current is flowing through the body diode of Q_{clamp} , it can be turned on after a short time (T_{delay_1}) in ZVS condition as shown in [Figure 4](#).

Now, before the switch pair Q1 and Q3 is turned on again, the clamp FET Q_{clamp} is turned off. Because the direction of the I_{clamp} has reversed and it is now flowing through the channel of the Q_{clamp} , I_{clamp} instantly comes to zero.

Because the current through the leakage inductor cannot change instantly, a portion of the current flowing through the FET Q_{clamp} , begins to flow through the body diode of FET Q1 and Q3. This begins to discharge the C_{OSS} of FETs Q1 and Q3 and causes ZVS to occur. After this, FETs Q1 and Q3 can be turned on under ZVS or close to ZVS condition, thereby reducing the turnon loss. The delay from the point of turnoff of the clamp FET Q_{clamp} and turnon of Q1 and Q3 is marked as T_{delay_2} in [Figure 4](#).

6.3.1.3 Boost Mode Working: Cold Start

Figure 5 shows the LV-side full-bridge converter along with the start-up clamp circuit.



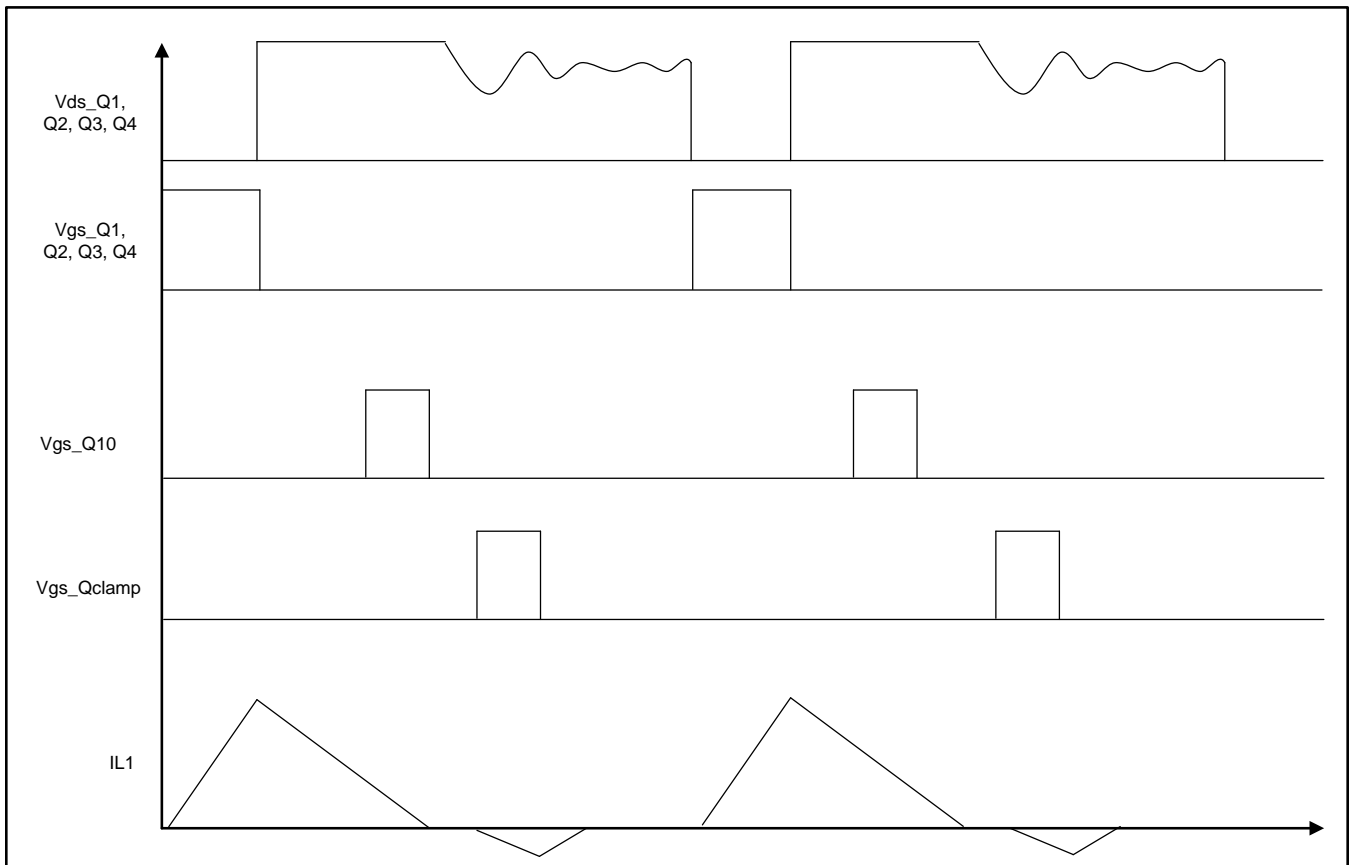
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Figure 5. Cold Start Clamp Circuit

During the system start-up, if the HV DC bus is completely discharged. The TIDA-00951 starts up using an additional flyback winding present on the inductor L1. In this mode, the LV-side full bridge does not work as a current-fed converter but as a flyback converter. It works in this mode until the HV bus reaches 270-V DC and then the system switches over to working as a current-fed converter.

In Figure 5, the MOSFETs Q1, Q2, Q3, and Q4 form the LV-side full bridge. Q_{clamp} and C_{clamp} form the active clamp. The flyback winding on the inductor L1 is used to temporarily charge a small capacitor, which is then boosted and fed to the HV DC bus output capacitors using the boost converter formed by Q10, D10, and L3.

Figure 6 shows the PWM waveforms of the LV MOSFETs Q1 to Q4, clamp MOSFET Q_{Clamp} , and the boost MOSFET Q10. The figure also shows the current-fed inductor current waveform and the drain-to-source voltage waveform of the low-side bridge MOSFET.



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Figure 6. TIDA-00951 Cold Start Clamp Circuit Working

All the MOSFETs on the LV bridge are turned on simultaneously. This charges the current-fed inductor. When these MOSFETs are turned off, the current in the current-fed inductor is transferred to the flyback winding and energy is stored in the capacitor C_{cold_start} .

The boosted MOSFET Q10 is then turned on to charge the boost inductor L3. This energy is then transferred to the HV bus output capacitors.

6.3.1.4 Current-Fed Inductor Calculation

The maximum input battery voltage $V_{\text{BAT_max}} = 60 \text{ V}$. The maximum voltage appearing across the primary winding of the transformer has to be chosen to be higher than this voltage so as to maintain the boost action of the current-fed power stage.

In order to maintain a minimum boost ratio, the reflected voltage on the primary when the HV bus is at 400 V is set as [Equation 1](#):

$$V_{\text{PRI}} = 1.1 \times V_{\text{BAT_max}} = 66 \text{ V} \quad (1)$$

The average voltage on the clamp V_{CLAMP} will be the same as the V_{PRI} .

By choosing the $V_{\text{PRI}} = 66 \text{ V}$, one can maintain sufficient voltage margin on the 100-V FET after accounting for voltage spikes at turnoff.

The switching frequency f_{SW} is selected as 100 kHz to get a good optimization in magnetic size reduction at the same time, maintaining high efficiency.

The maximum output power of the system is $P_{\text{OUT_max}} = 2 \text{ kW}$. Assuming a 92% efficiency, this gives the maximum input power as $P_{\text{IN_max}} = 2 \text{ kW}/0.92 = 2.173 \text{ kW}$.

$$P_{\text{IN_max}} = \frac{P_{\text{OUT_max}}}{0.92} = 2173 \text{ W} \quad (2)$$

The average maximum input current $I_{\text{in_max}} = P_{\text{in_max}} / V_{\text{BAT_min}} = 60.3 \text{ A}$.

$$I_{\text{IN_max}} = \frac{P_{\text{IN_max}}}{V_{\text{BAT_max}}} = 60.3 \text{ A} \quad (3)$$

The design equations for the current-fed inductor (L1) are similar to that of a boost converter. The two parameters that need to be used to calculate the value of the current-fed inductor are $D_{\text{MAX_overlap}}$ and $I_{\text{IN_maxripple}}$.

The $D_{\text{MAX_overlap}}$ defines the period for which the four full-bridge MOSFET on the LV side are on simultaneously. In order to calculate this, D_{MAX} needs to be calculated first.

D_{MAX} can be calculated using [Equation 4](#).

$$V_{\text{PRI}} = \frac{V_{\text{BAT_min}}}{2(1 - D_{\text{MAX}})} \quad (4)$$

This leads to $D_{\text{MAX}} = 0.728$.

The $D_{\text{MAX_overlap}}$ is given by [Equation 5](#):

$$D_{\text{MAX_overlap}} = D_{\text{MAX}} - 0.5 = 0.228 \quad (5)$$

The maximum ripple current is set as [Equation 6](#):

$$I_{\text{IN_maxripple}} = 0.3 \times I_{\text{IN_max}} = 18.1 \text{ A} \quad (6)$$

Substituting the known values for [Equation 7](#), L1 can be calculated.

$$L1 = \frac{V_{\text{BAT_min}} \times D_{\text{MAX_overlap}}}{f_{\text{SW}} \times I_{\text{IN_maxripple}}} = 4.5 \text{ } \mu\text{H} \quad (7)$$

The peak current in the inductor can be calculated as [Equation 8](#):

$$I_{\text{IN_pk}} = I_{\text{IN_max}} + \frac{I_{\text{IN_maxripple}}}{2} = 69.4 \text{ A} \quad (8)$$

6.3.1.5 Transformer Calculation

The turns ratio for the transformer is given as $N_s / N_p = V_{BUS_max} / V_{PRI} = 400 / 66 = 6:1$

The primary (LV side) RMS current through the transformer can be given by Equation 9:

$$I_{TX_PRI_rms} = \sqrt{\left(3 \times (I_{IN_max})^2 + I_{IN_max\,ripple}^2\right) \times \frac{(3 - 2 \times D_{min})}{\frac{4}{3}}} \tag{9}$$

$$I_{TX_PRI_rms} = 47 \text{ A}$$

The required turns ratio of the transformer is given by Equation 10. The turns ratio is chosen as 6 to help account for the conduction losses on the LV full bridge.

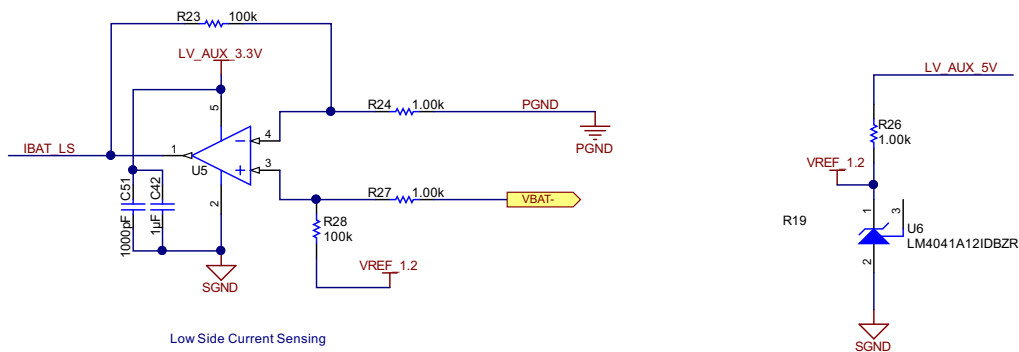
$$\frac{N_s}{N_p} = \frac{380}{66} = 5.75 \tag{10}$$

The secondary (HV side) RMS current through the transformer is estimated to be $I_{TX_SEC_rms} = 7.5 \text{ A}$.

6.3.1.6 Low-Side Current Sensing Circuit

In the TIDA-00951, low-side current sensing is implemented to measure the battery current on the LV side using the OPA376.

Because the battery current is bidirectional in nature, the output of the OPA376 is 1.2 V by using the LM4041A12 shunt voltage reference. This is shown in Figure 7.



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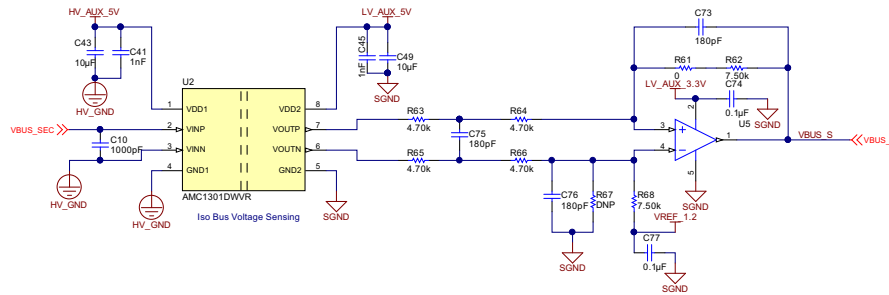
Figure 7. Low-Side Current Sensing Circuit Schematic

The OPA376 difference amplifier measures the current across a 0.25-mΩ current sense resistor formed by the parallel combination of resistors of R20 and R29.

6.3.1.7 Isolated Voltage Sensing

The control electronics (TIDA-01281) on the TIDA-00951 board is referred to the LV battery-side ground. In order to sense the voltage across the isolated 400-V bus, an isolation amplifier circuit based around the AMC1301 isolated amplifier and OPA376 op amp is used.

The differential output of the AMC1301 is scaled and converted into a single-ended output for connecting directly to the MCU. **Figure 8** shows this circuit.



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Figure 8. Isolated Voltage Sensing Circuit Schematic

7 Getting Started Hardware

7.1 Hardware

This section explains the power supply requirement and connectors used to set up the TIDA-00951 board for testing.

For testing the TIDA-00951, three other TI Designs are used. The TIDA-01281 is a TMS320F28033-based control and communication card. It is used as the control unit for TIDA-00951. The TIDA-01159 based on the UCC21520 is the half-bridge gate driver that will be used to drive the HV full-bridge MOSFET. The TIDA-01141 is the high-side current sensing card based on the INA240 and is used for sensing the inductor current.

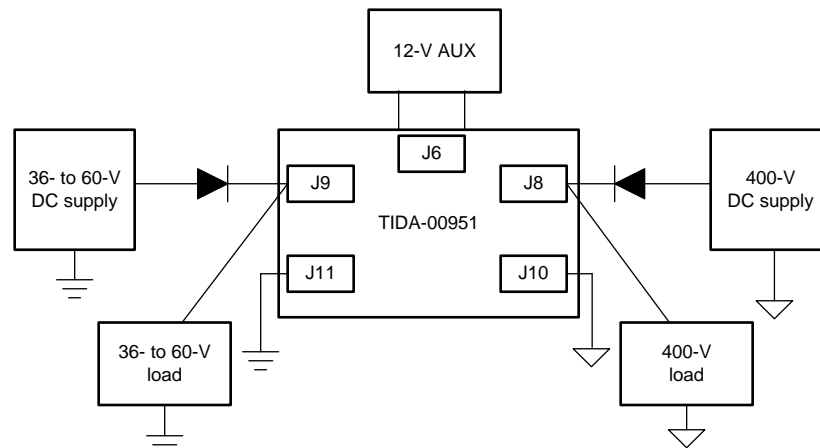
Mount the TIDA-00951 on connector J5. Mount the TIDA-01141 on connector J14.

The TIDA-00951 requires two TIDA-00159 boards on the HV-side full bridge. Each TIDA-01159 board needs to be mounted on three connectors. The connectors J3, J1, and J4 form one set of connectors on which one of the TIDA-01159 board is mounted. The connectors J2, J13, and J15 form the other set on which the second TIDA-01159 board is mounted.

For providing auxiliary power to the TIDA-00951 board, a 12-V DC supply needs to be connected to connector J6.

7.2 Test Setup

This section describes the test setup required and the test procedure. For conducting bidirectional power transfer and mode change over experiments, the test setup is shown in [Figure 9](#).



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Figure 9. Test Setup for Bidirectional Power Flow

7.3 Test Equipment Needed to Validate Board

- DC source: 0- to 400-V DC, 5 A rated
- DC source: 0- to 60-V DC > 70 A rated
- DC source: 12 V, 1 A
- Four-channel digital oscilloscope
- Current probe: 0.30 A, 50 MHz
- Electronic or resistive load capable of working up to 400 V, 5 A
- Electronic or resistive load capable of working up to 60 V, 16 A

7.4 Test Procedure

1. Prepare the test setup as shown in [Figure 9](#).
2. Connect one DC supply on the battery input side (connectors J9 and J11) through the diode with voltage set anywhere from 36 to 60 V.
3. Connect another DC supply on the bus input side (connectors J8 and J10) through a diode with voltage set to 380 V.
4. Connect an electronic load to the bus input terminal with load set to draw 100 W.
5. Connect an electronic load to the battery input terminal with load set to draw 100 W.
6. Connect a DC fan and position it in such a way that the TIDA-00951 board receives about 400 LFM.
7. Connect a 12-V auxiliary supply to connector J6.
8. Turn on the DC supply connected to the bus input terminal.
9. Turn on the DC supply connected to the battery input terminal.
10. The TIDA-00951 will start working in charger mode and start supplying power to the electronic load on the battery side.
11. Now disconnect the DC power supply connected to the bus input terminal.
12. The TIDA-00951 board will start working in the backup supply mode and power the load connected to the bus input terminal.
13. Now increase the load in steps up to 2 kW to test the backup supply mode.
14. The necessary functional performance characteristics can be measured now.
15. Turn off the DC supply and disconnect the DC supply from the board.

8 Testing and Results

8.1 Boost Mode Hard Start at 36-V Battery Voltage

In [Figure 10](#), the yellow waveform is the drain-to-source voltage of an LV MOSFET, and the blue waveform is the current-fed inductor current. The maximum spike on the drain-to-source voltage reaches < 70 V. The inductor current is in excess of 50 A. This test is conducted to show that the maximum spike on the LV MOSFET remains well under the 100-V rating of the MOSFET.

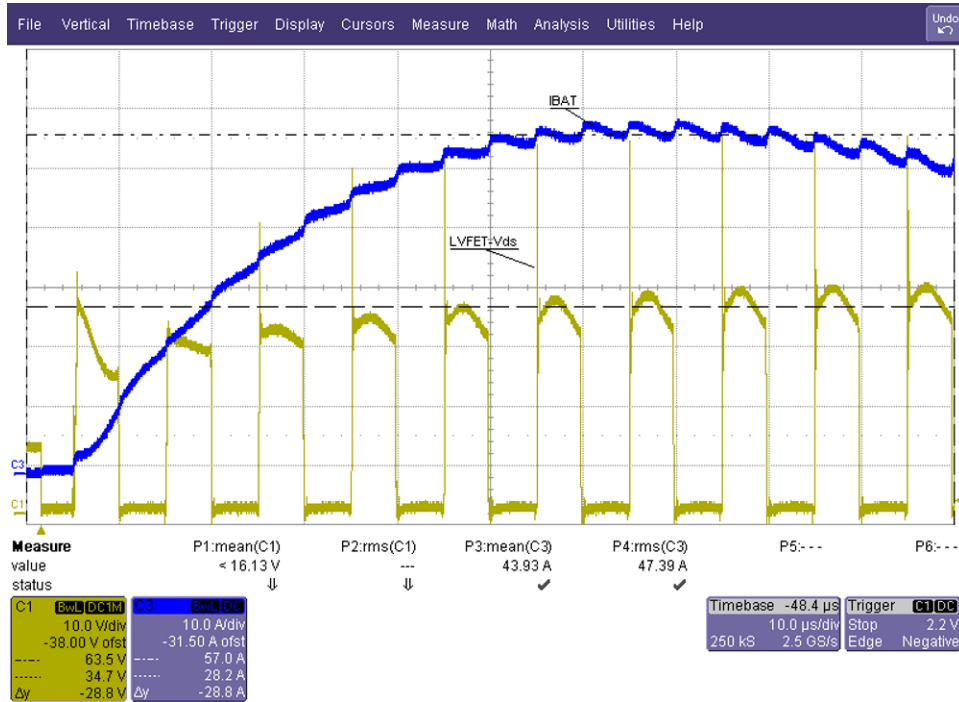


Figure 10. Boost Mode Hard Start at 36-V Battery Voltage

A zoomed waveform for hard startup at a 36-V battery voltage is shown in Figure 11.

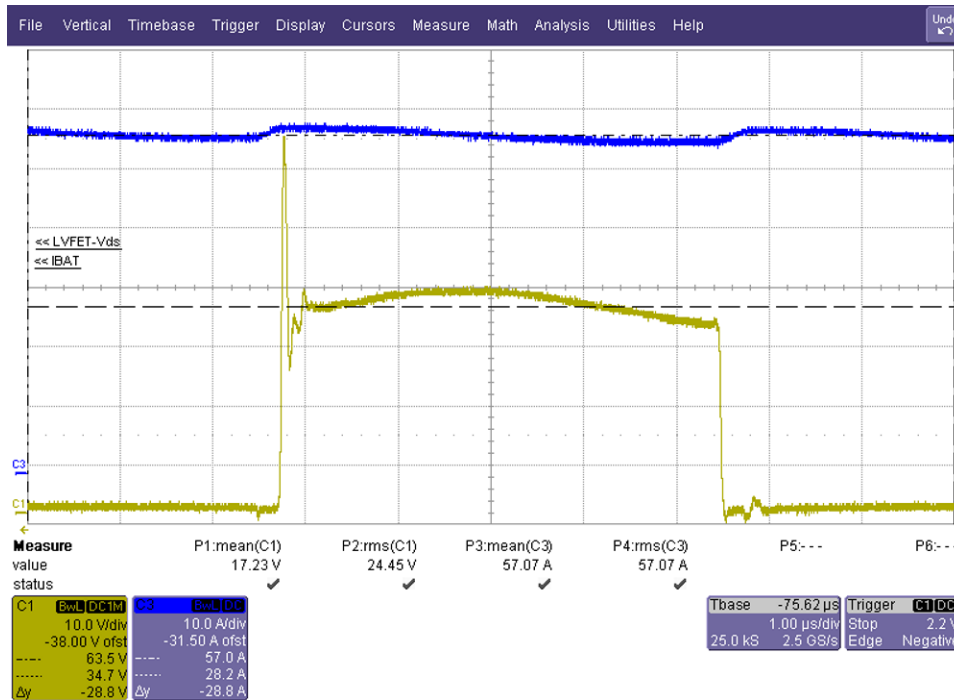


Figure 11. Boost Mode Hard Start at 36-V Battery Voltage (Zoomed In)

8.2 Boost Mode Hard Start at 60-V Battery Voltage

In Figure 12, the yellow waveform is the drain-to-source voltage of an LV MOSFET, and the blue waveform is the current-fed inductor current. The maximum spike on the drain-to-source voltage reaches < 65 V.

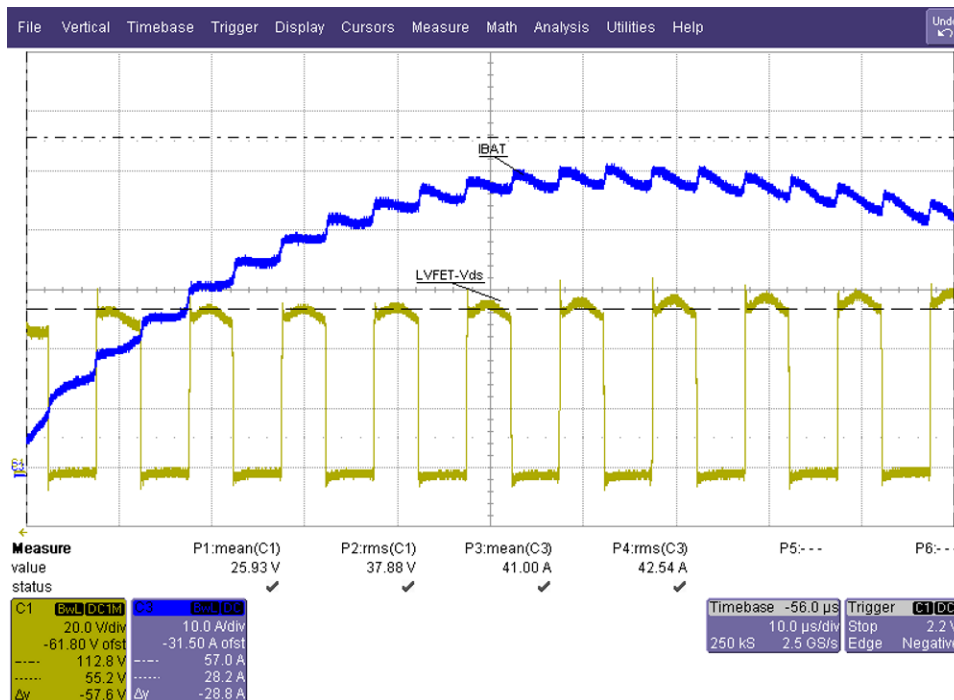


Figure 12. Boost Mode Hard Start at 60-V Battery Voltage

A zoomed in startup waveform is shown in Figure 13. The voltage spike at turnoff does not cross 10 V.

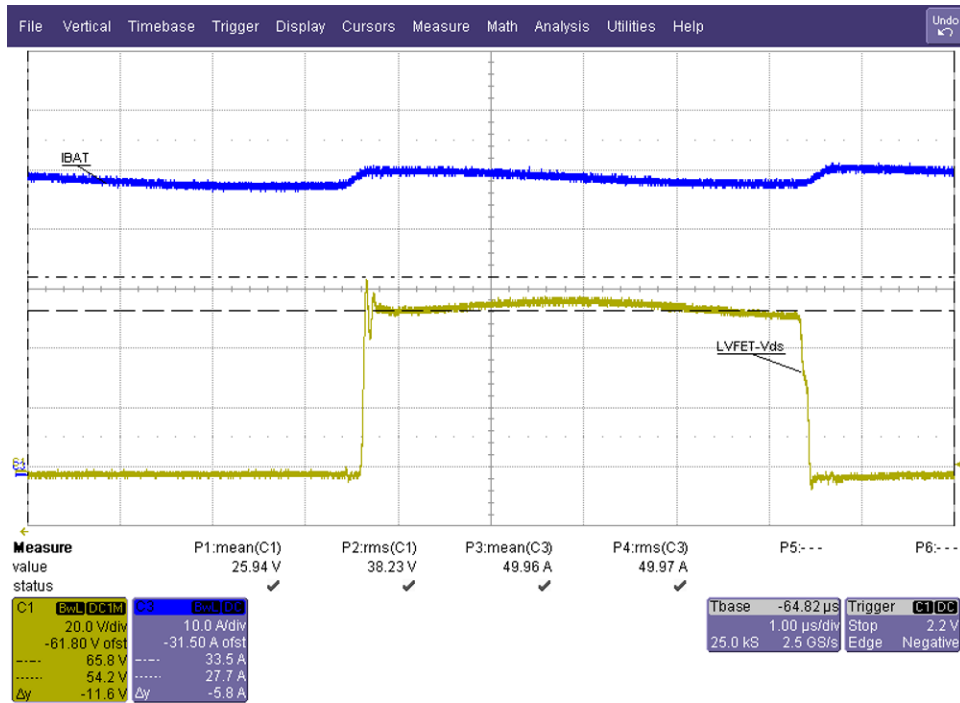


Figure 13. Boost Mode Hard Start at 60-V Battery Voltage (Zoomed In)

8.3 Boost Mode ZVS Waveform

Figure 14 and Figure 15 show the boost mode working waveforms. Figure 14 shows a full ZVS operation, and Figure 15 shows a near ZVS turnon. The yellow trace is the LV MOSFET drain-to-source voltage, the blue trace is the current-fed inductor current, and the rose waveform is the gate driver output.

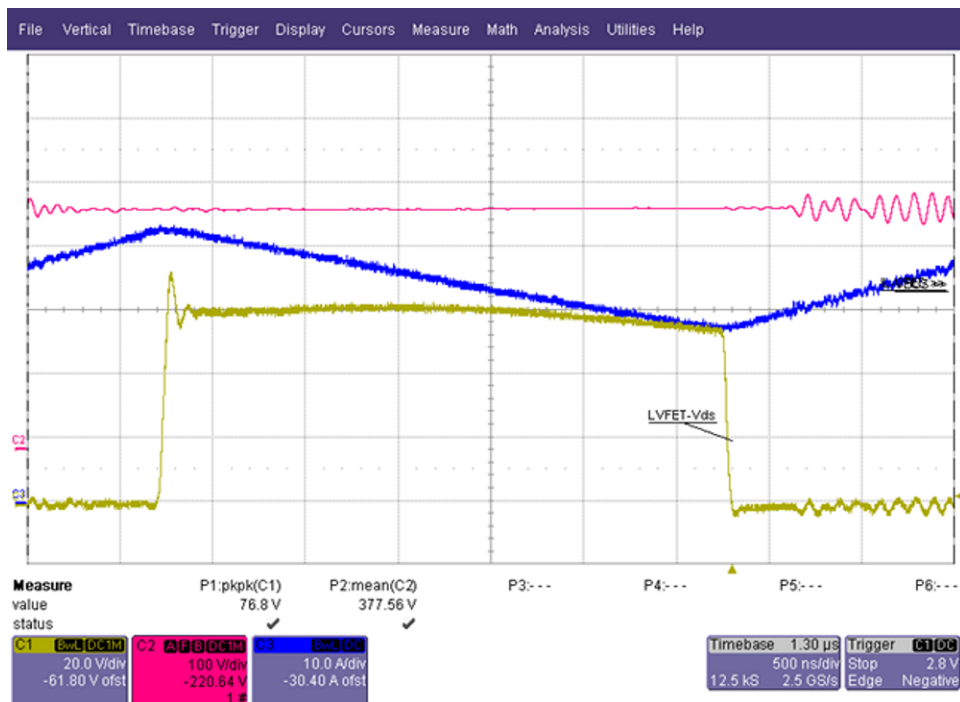


Figure 14. Boost Mode Working Waveform With ZVS Turnon

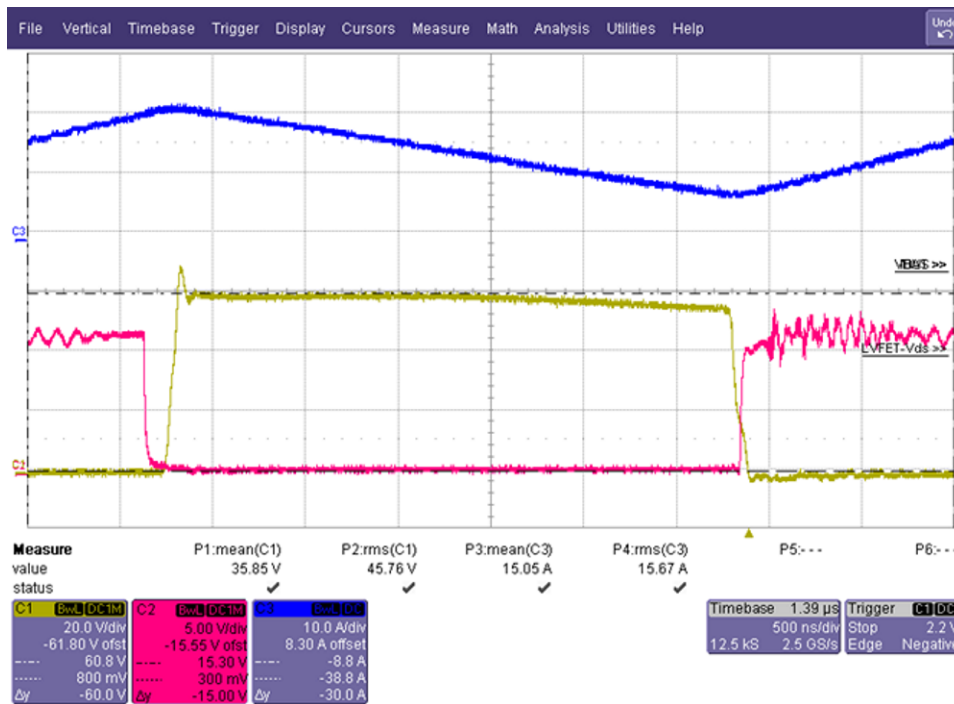


Figure 15. Boost Mode Working Waveform With Valley Switching Turnon

When the inductor current increases, one can get ZVS operation at turnon. At lower input currents, the LV MOSFET is turned close to 0 V at turnon.

8.4 Active Clamp Working Waveform

The LV MOSFET drain-to-source voltage and gate voltage is shown along with the active clamp current in Figure 16. When the LV MOSFET turns off, the current through it transfers to the active clamp.

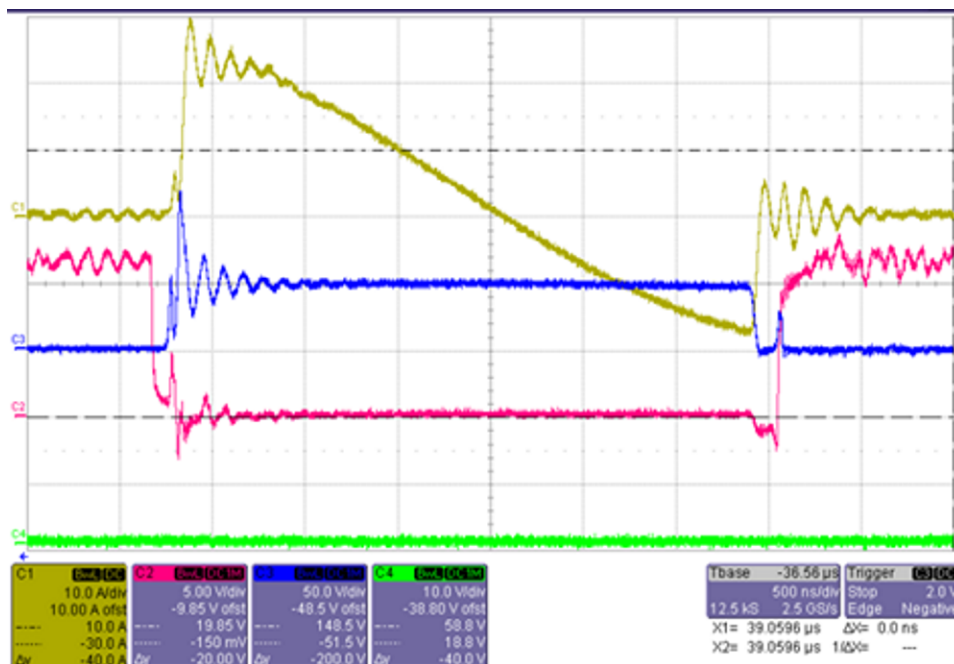


Figure 16. TIDA-00951 Active Clamp Working Waveform

Before the MOSFET is turned on again, the clamp MOSFET is turned off; this causes the current through the clamp to come to zero. Because the current through the transformer leakage inductor cannot change instantaneously, the current that was flowing through the clamp circuit (clamp MOSFET) begins to free wheel through the LV MOSFET's body diode, thereby enabling it to turn at the ZVS condition.

8.5 Buck Mode Working Waveform

Figure 17 shows the switching waveform on the LV MOSFETs when operated in the buck mode. The LV MOSFET turns on under ZVS condition.

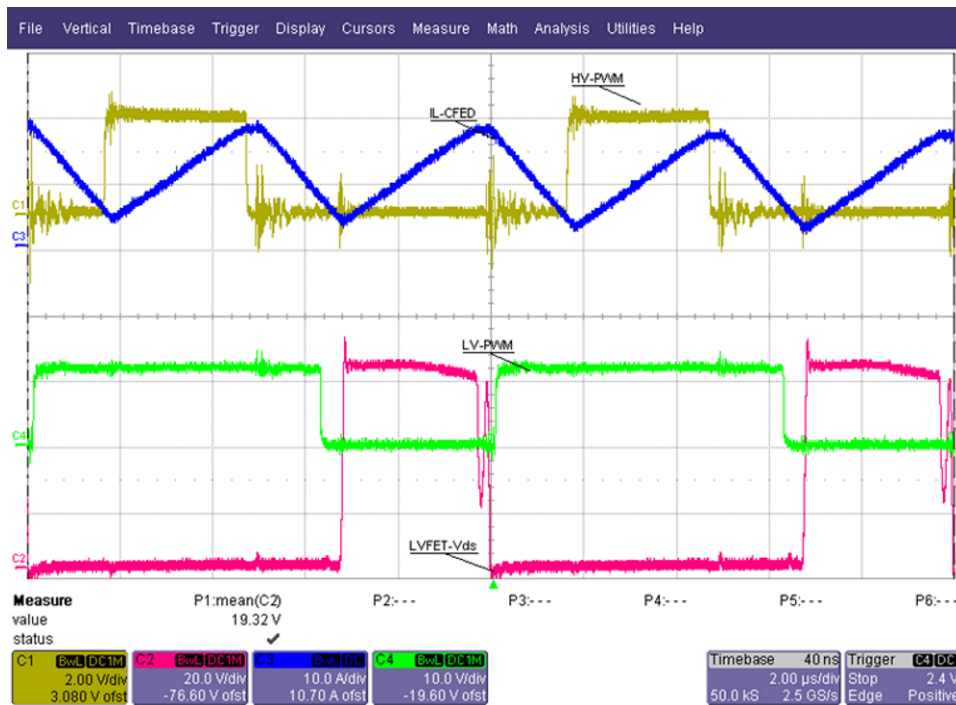


Figure 17. Buck Mode Switching Waveform

The yellow trace represents the HV-side MOSFETs gate drive PWM input signal; the blue trace represents the current-fed inductor; the green trace is the PWM input signal fed to the LV gate driver; and the red waveform is the LV MOSFET's drain-to-source voltage. The red waveform goes to 0 V before the green PWM trace goes high.

8.6 Buck-to-Boost Mode Transition Waveform

Initially, the system works in buck mode as a battery charger. In this mode, it takes power from a 400-V DC bus and charges the LV battery pack.

When a power failure occurs on the 400-V bus, the voltage on the 400-V bus starts to drop. This triggers a mode transition from buck-to-boost mode, where the power is taken from the battery pack and fed into the 400-V bus.

The timing for this transition is very critical because it determines how quickly and seamlessly the system can provide backup power and also the sizing of the capacitors on the 400-V bus required for providing the necessary holdup time.

Figure 18 shows the mode transition. When the 400-V bus voltage falls below 370 V, the TIDA-00951 stops charging the battery and goes into a boost soft start. When the 400-V bus voltage falls below 360 V. It goes into hard start boost mode and immediately pumps the required power to bring the 400 V bus voltage back to 370 V and regulates it at this point. The red trace represents the 400-V bus voltage, the blue trace represents the inductor current, the green trace is the LV MOSFET PWM signal, and the yellow trace represents the HV-side MOSFET PWM signal.

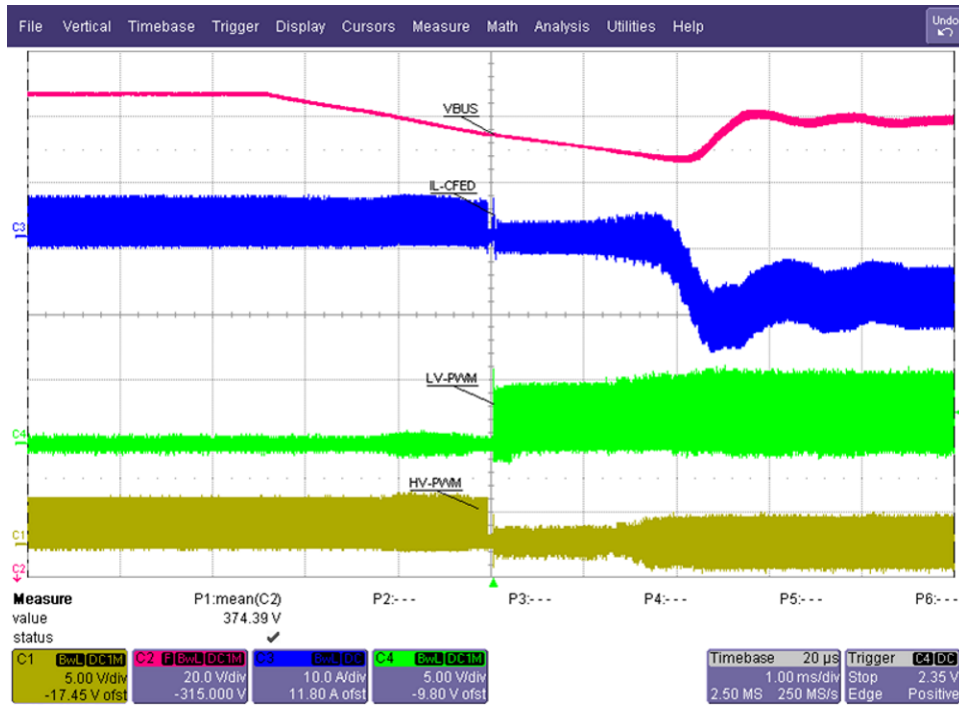


Figure 18. TIDA-00951 Battery Charging to Backup Mode Transition

Figure 19 shows the zoomed out mode transition waveform, which shows the actual mode transition period of 80 μ s.

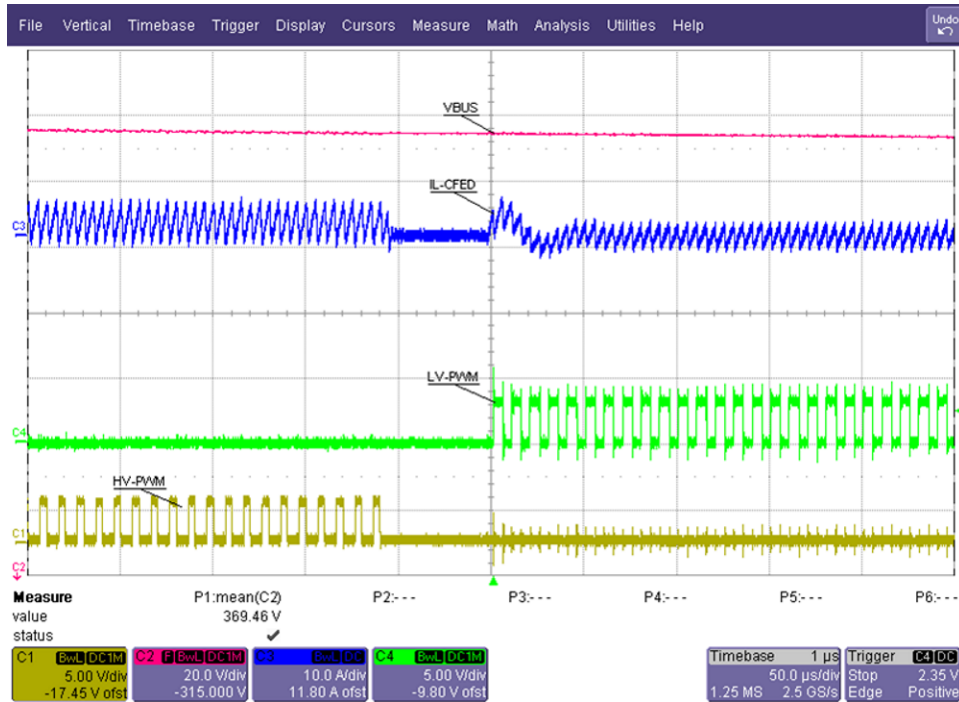


Figure 19. TIDA-00951 Battery Charging to Backup Mode Transition Zoomed

8.7 Cold Start Waveform

When the TIDA-00951 is started for the first time, the 400-V bus can be completely discharged. This is a special situation and does not occur during normal working conditions.

In order to startup under this condition, the TIDA-00951 uses a modified Weinberg clamp to pre-charge the 400-V bus to 270 V. After charging to 270 V, the system moves complete the startup is normal boost mode operation. In Figure 20, the red trace represent the 400-V bus voltage, the green trace is the PWM signal sent to the modified Weinberg clamp, and the blue trace is the current taken from the battery for pre-charging process.

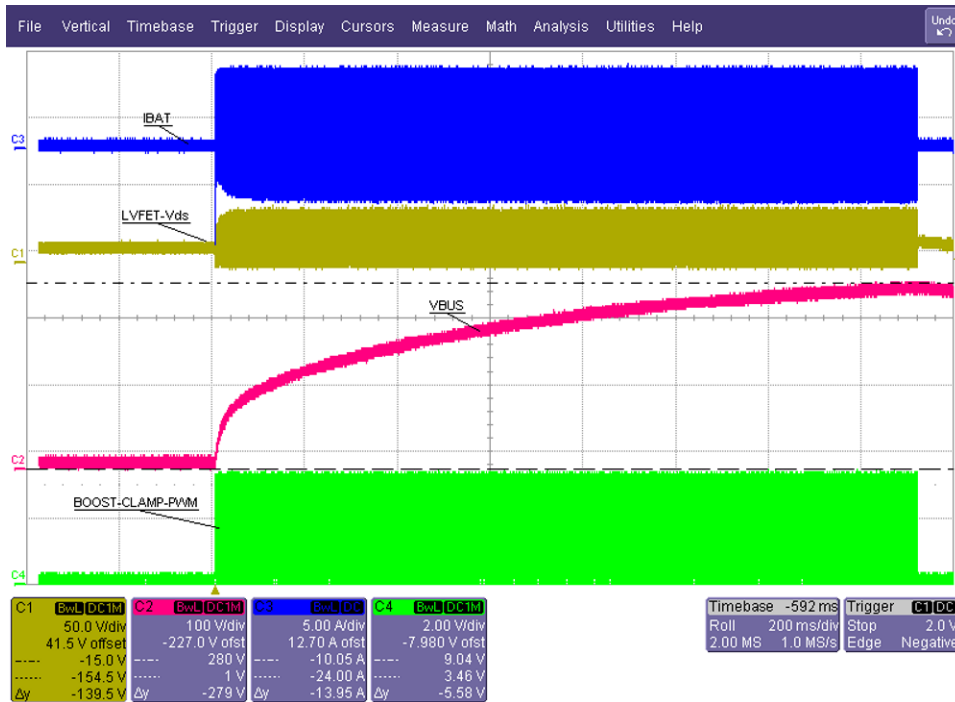


Figure 20. Cold Start Using Weinberg Clamp

Figure 21 shows the zoomed in switching waveform during the cold start process. The LV (battery side) full bridge is being operated in DCM, and the energy in the current-fed inductor is transferred to the secondary through the Weinberg clamp. This energy stored in a small capacitor on the HV side, which is boosted to pre-charge the 400-V DC bus capacitors. The green trace shows the PWM signals for the auxiliary low-power boost converter.

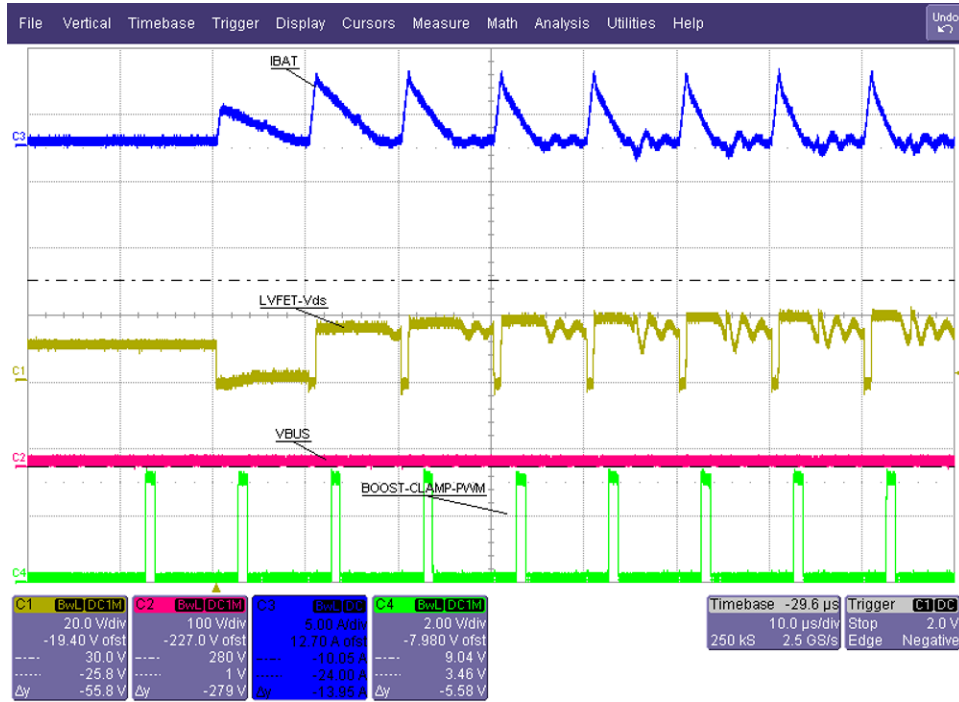


Figure 21. Cold Start Working Waveform (Zoomed)

8.8 Boost Mode Efficiency

Figure 22 shows the boost mode output power versus efficiency data captured for various battery voltage.

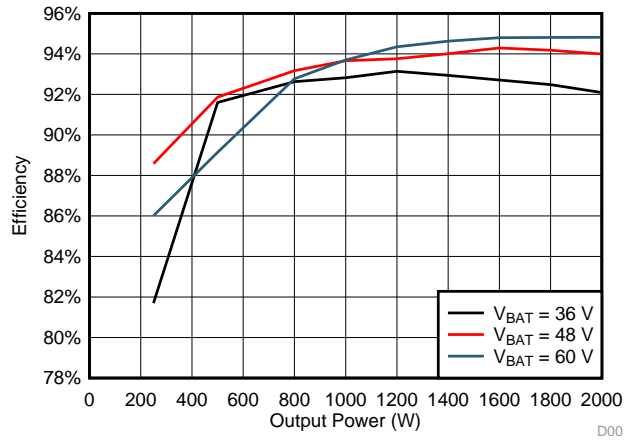


Figure 22. Boost Mode Output Power versus Efficiency

8.9 Buck Mode Efficiency

Figure 23 shows the buck mode efficiency at various battery voltage and charging current. The 400-V bus voltage was fixed at 380-V DC for conducting this test.

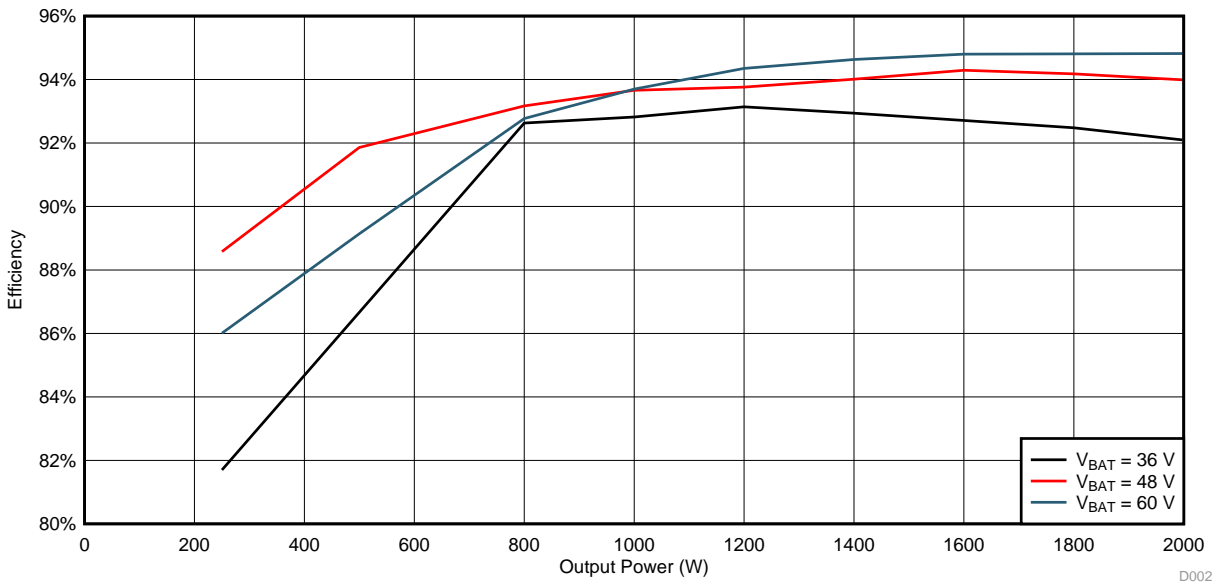


Figure 23. Buck Mode Charging Current versus Efficiency

8.10 Thermal Images

The thermal image of the TIDA-00951, working at 1500 W is shown in [Figure 24](#).

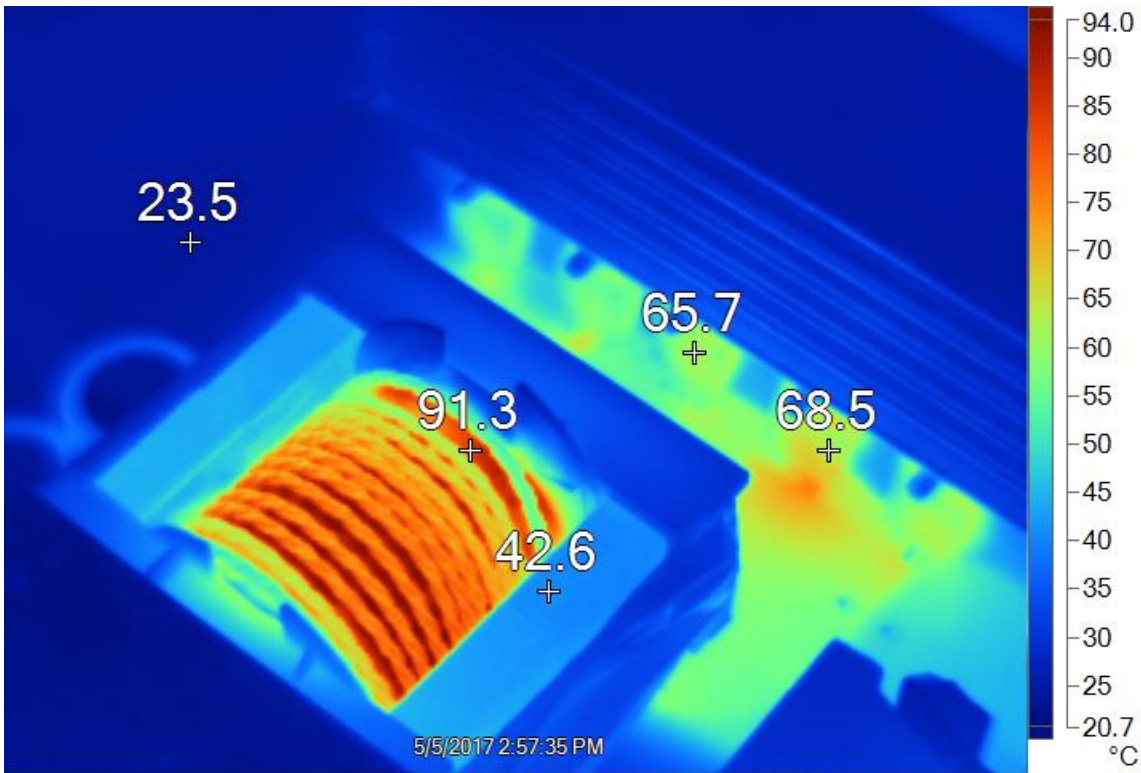


Figure 24. TIDA-00951 Thermal Image at 1500 W

The maximum temperature on the board is on the isolation transformer. The board is force cooled with a 400LFM airflow.

9 Design Files

9.1 Schematics

To download the schematics, see the design files at [TIDA-00951](#).

9.2 Bill of Materials

To download the bill of materials (BOM), see the design files at [TIDA-00951](#).

9.3 PCB Layout Recommendations

For the power stage layout:

1. Minimize the loop formed by the LV full bridge, the active clamp, and the transformer primary to keep the leakage inductances very low and the loop area small.

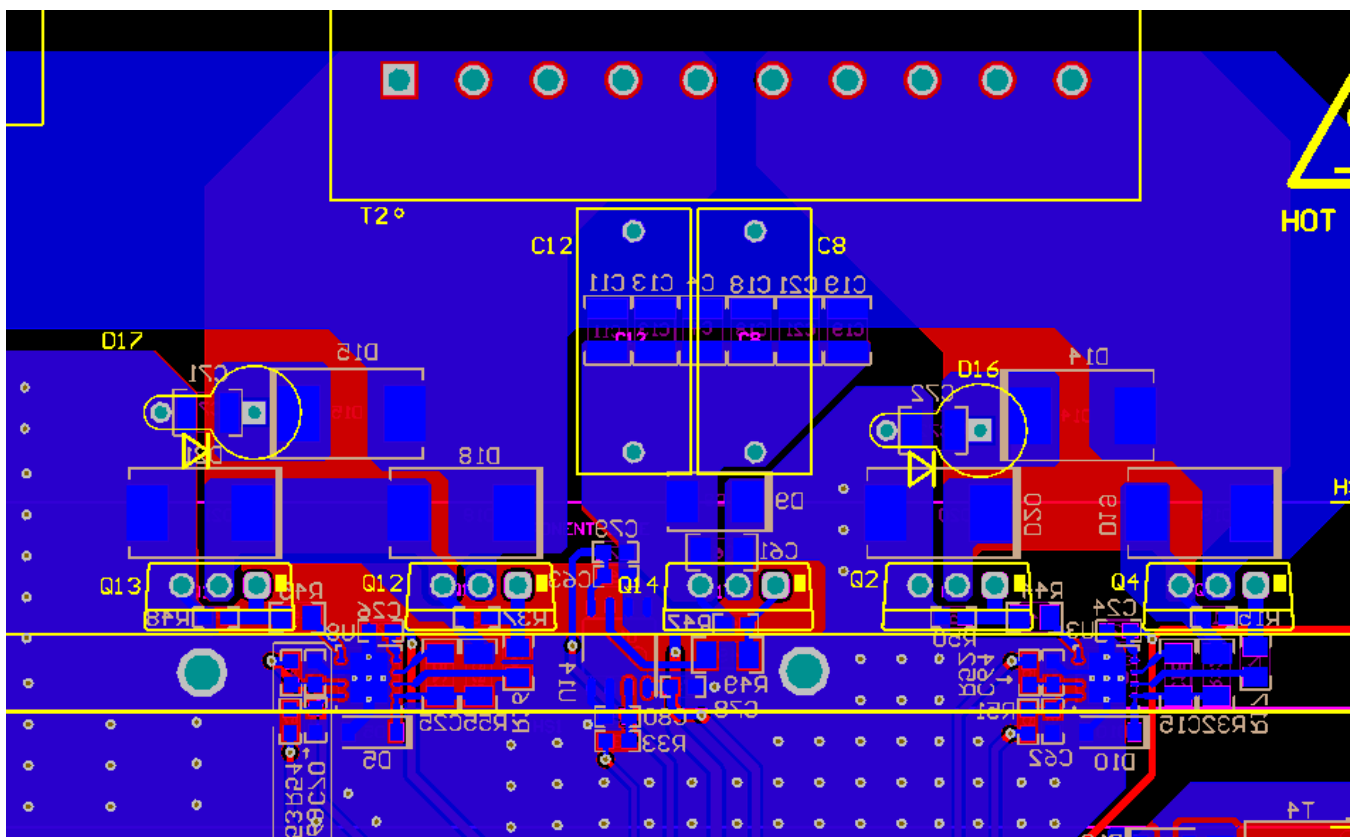


Figure 25. LV Full-Bridge Layout Including Active Clamp

2. The traces have to be as thick as possible to minimize the trace inductances.
3. Place the additional RC snubber if required in such a way as to minimize the spikes due to the FET lead inductances.
4. The loop formed on the secondary side between the transformer secondary winding, HV full-bridge FETs, and the filter capacitor has to be as small as possible.
5. Place the gate driver on the LV side very close to the FET and at almost equal distance from the top and bottom FET in each arm (see [Figure 26](#)).

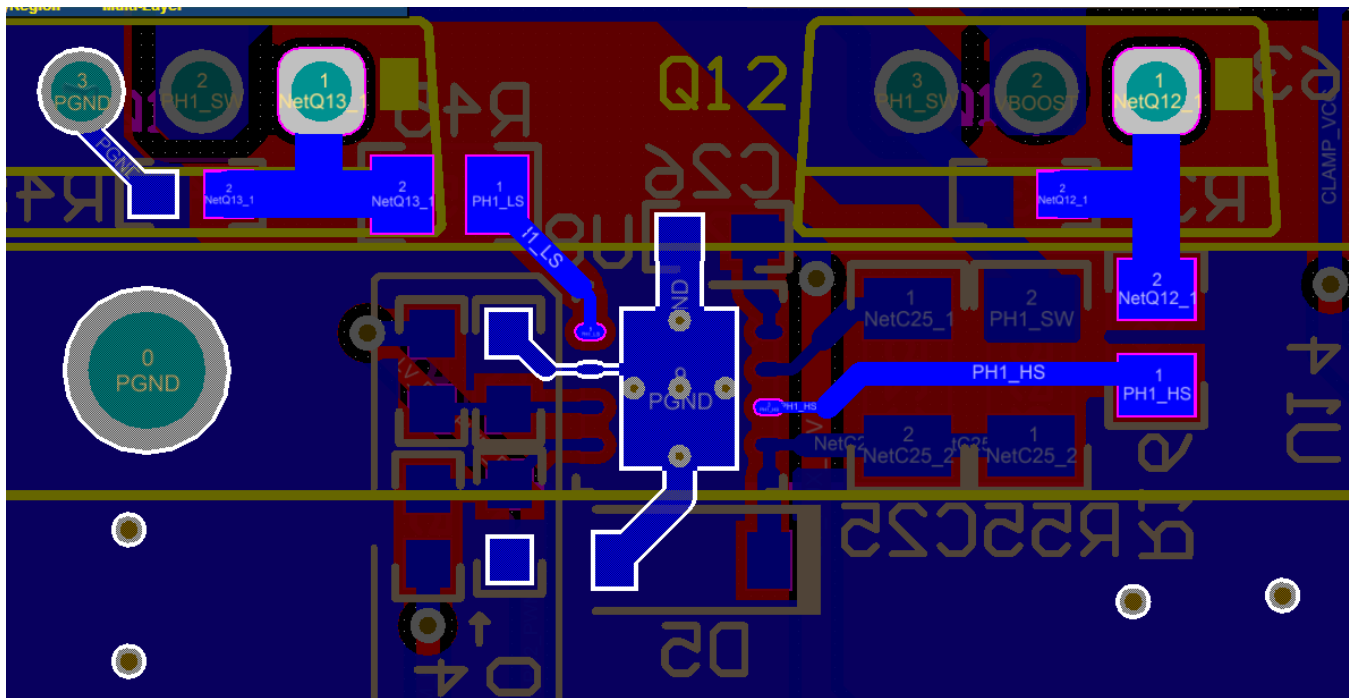


Figure 26. Low-Voltage Side Half-Bridge Gate Driver Placement

6. The GND pad on the bottom of the gate driver IC should be connected to a solid plane on the PCB to help with thermal management for the gate driver and reduce the spikes on the gate driver IC's pins.
7. Use multiple low ESR ceramic capacitors in the battery input section of the board to support the required ripple current.

For current sensing:

1. Take a Kelvin connection from the current sense resistor as much as possible to connect to the amplifier section.
2. Place the low-pass filter components just before the input of the amplifier.
3. The lines taken from the current sensor resistor need to be shielded with the GND plane wherever possible to limit noise pickup on the lines.

A snapshot of the low-side current sense implementation is shown in [Figure 27](#).

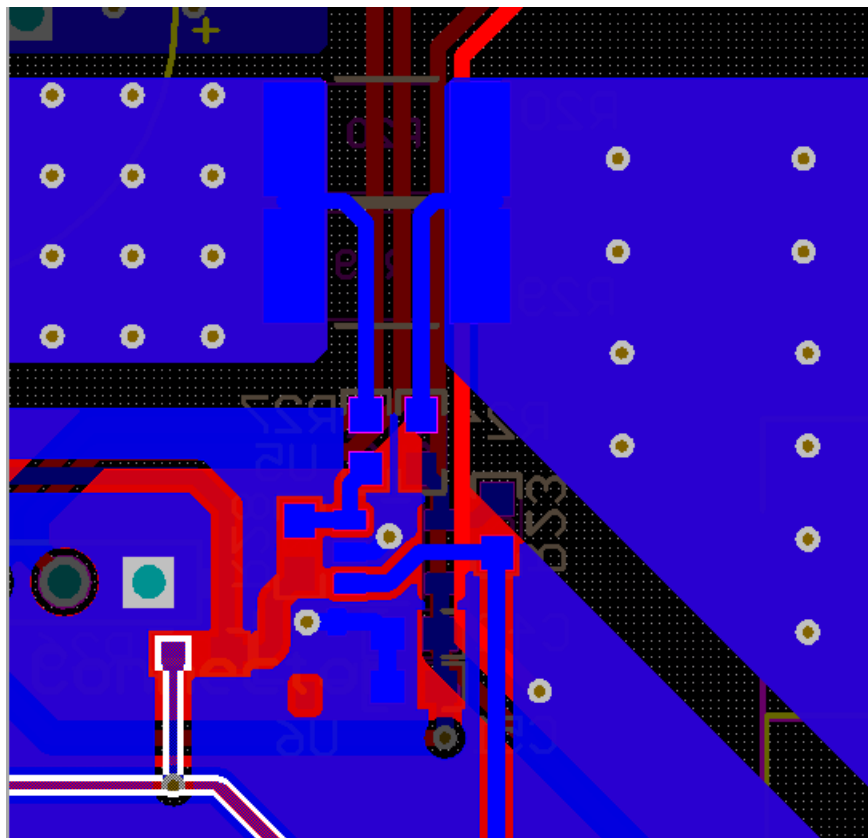


Figure 27. High-Side Battery Current Sensing Circuit Layout

For the control section:

1. Buffer the PWM outputs from the control card before connecting them to the gate driver input.
2. Separate the GND of the control card from the power GND to make sure that the switching current flowing in the power GND does not affect the PWM signals being fed to the gate drivers.

9.3.1 Layout Prints

To download the layer plots, see the design files at [TIDA-00951](#).

9.4 Altium Project

To download the Altium project files, see the design files at [TIDA-00951](#).

9.5 Gerber Files

To download the Gerber files, see the design files at [TIDA-00951](#).

9.6 Assembly Drawings

To download the assembly drawings, see the design files at [TIDA-00951](#).

10 Software Files

To download the software files, see the design files at [TIDA-00951](#).

11 Related Documentation

1. IEEE, *Operation principles of bi-directional full-bridge DC/DC converter with unified soft-switching scheme and soft-starting capability*, 15th Annual IEEE Applied Power Electronics Conference and Exposition, 2000
2. IEEE, *Extended Range ZVS Active-Clamped Current-Fed Full-Bridge Isolated DC/DC Converter for Fuel Cell Applications: Analysis, Design, and Experimental Results*, IEEE Transactions on Industrial Electronics (Volume: 60, Issue: 7, July 2013)
3. Texas Instruments, *Bidirectional DC-DC Converter*, TIDM-BIDIR-400-12 Design Guide (TIDUA17)
4. IEEE, *Isolated full bridge boost DC-DC converter designed for bidirectional operation of fuel cells/electrolyzer cells in grid-tie applications*, 15th European Conference on Power Electronics and Applications (EPE), 2013

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12 About the Authors

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