TI Designs

Leakage Current Measurement Reference Design for Determining Insulation Resistance

Design Overview

This TI design provides a reference solution to measure the insulation resistance up to 100 MΩ. The design has an onboard, isolated 500-V DC power supply and an isolated signal conditioning circuit to measure the leakage current and then determine the insulation resistance.

Design Resources

TIDA-00440	Tool Folder Containing Design Files
INA225	Product Folder
AMC1200	Product Folder
CSD13202Q2	Product Folder
ISO7640FM	Product Folder
INA333	Product Folder
TS5A23157	Product Folder
LM5160	Product Folder
TLV1117-50	Product Folder
LP2985A-50	Product Folder
UCC28711	Product Folder

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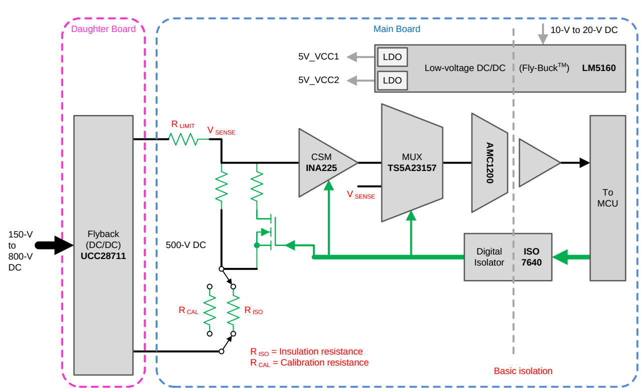
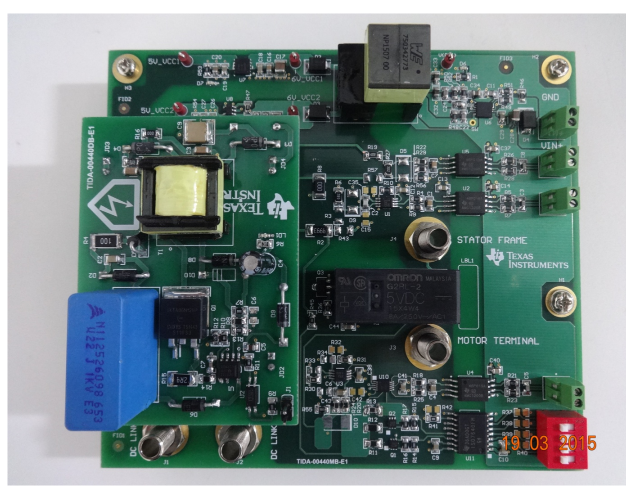
Design Features

- Leakage Current Measurement Circuit With Option for Programmable Current Sense Amplifier and Switchable Shunt Resistors
- Range of Measurement: 0 Ω to 100 MΩ
- Measurement Accuracy: 5% (Uncalibrated)
- Test Voltage Level Derived from IEEE 43-2000
- Onboard Isolated 500-V Power Supply to Measure Insulation Resistance
- Provision for Calibration Resistor on Board
- Provision for Polarization Index Measurement Based on Test Duration
- Basic Isolation for Measurement Circuit
- Onboard Relay to Disconnect the Insulation Measurement Circuit When Not in Operation

Featured Applications

- Industrial Drives
- Variable Speed AC/DC Drives
- Servo Drives
- Transformers
- Solar Inverters





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1 Introduction

The deterioration of insulation is one of the primary causes of electrical equipment failure. This TI design provides a reference solution to measure the insulation resistance up to 100 MΩ with an uncalibrated accuracy of 5%. The reference design uses an onboard isolated 500-V DC power supply and isolated signal conditioning circuit to measure the leakage current for determining the insulation resistance.

1.1 Importance of Insulation Measurement

Insulating materials play a critical role in the life of electrical equipment. The failure of insulation, while in service, may cause significant damage to equipment and to the system to which the equipment is connected. Insulation failure can cause dangerous voltage, fire, high fault current and explosion, damage to equipment and property, personnel injury, and fatal accident. By applying insulation tests, the user can identify deteriorated insulation before any failure occurs.

1.2 Causes of Insulation Degradation

The main causes of insulation failure are dielectric contamination, temperature cycling, excessive overloads, excessive voltage stress due to overvoltage, and aging.

1. Thermal stress: Running the machine in excessively hot or cold conditions causes over expansion or contraction of the insulation, which may result in cracks and failures. However, thermal stresses are also incurred every time a machine starts or stops. Unless the machinery is designed for intermittent use, every stop and start adversely affects the aging process of the insulation.
2. Electric stress: Insulation is designed for a particular application. Overvoltages cause abnormal stress within the insulation, which can lead to cracking or delamination of the insulation.
3. Voltage unbalance: When the voltage between all three phases is equal (balanced), the current values are the same in each phase winding. When the voltages between the three phases (AB, BC, and CA) are not equal (unbalanced), the current increases dramatically in the motor windings. If the user allows this increase to continue for too long, the motor is damaged.

Normal cycles of operation lead to aging through the previously mentioned mechanisms. The aging of insulation is a slow process of degradation as these factors interact with each other in a gradual spiral of decline. At some point, depending on both original and operating conditions, the decline may speed up significantly.

2 System Description

The TIDA-00440 reference design uses a mechanism to find the leakage current and detect the failure in insulation. The leakage current is measured by applying a fixed, high voltage DC and by measuring the leakage current flowing through the shunt. The high voltage DC is generated using an onboard power supply based on a flyback topology, which takes a wide range of DC input voltage from 150-V DC to 800-V DC. The functionality of finding insulation resistance is implemented using two boards: the main board (TIDA-00440MB), which is the signal conditioning circuit , and the daughter board (TIDA-00440DB), which has an Isolated 500-V DC.

One important point to note is that the test levels, test voltage, and insulation levels derive from the IEEE standard IEEE43-2000 (*IEEE Recommended Practice for Testing Insulation Resistance of Rotating Machinery [1]*). This standard describes a recommended procedure for measuring insulation resistance and describes the typical insulation resistance characteristics of rotating machine windings and how these characteristics indicate winding condition. This standard recommends the minimum acceptable values of insulation resistance for AC and DC rotating machine windings. Using this standard as a base, Table 1 makes the following judgments:

Table 1. Insulation Resistance

INSULATION RESISTANCE	JUDGEMENT
100 MΩ or higher	Acceptable.
10 to 100 MΩ	The winding has begun deteriorating. There is no problem with the performance at present. Be sure to perform a periodic inspection.
1 to 10 MΩ	The winding has considerably deteriorated. Special care is required. Be sure to perform a periodic inspection.
Lower than 1 MΩ	Unacceptable.

3 Design Features

The TIDA-00440 reference design features the following characteristics:

1. Leakage current measurement circuit with option for:
   (a) Programmable current sense amplifier: INA225 has four gain-settings selected based on the GS0 and GS1
   (b) Switchable shunt resistors
2. Facilitates online insulation measurement during installation and maintenance testing
3. Range of measurement: 0 Ω to 100 MΩ
4. Measurement accuracy: 5% (Uncalibrated)
5. Test voltage Level derived from IEEE 43-2000 (*Recommended Practice for Testing Insulation Resistance of Rotating Machinery*)
6. Onboard isolated 500-V power supply to measure insulation resistance
7. Provision for calibration resistor on board
8. Provision for polarization index measurement based on test duration
9. Basic isolation for measurement circuit
10. Onboard relay to disconnect the insulation measurement circuit when not in operation

4 Block Diagram

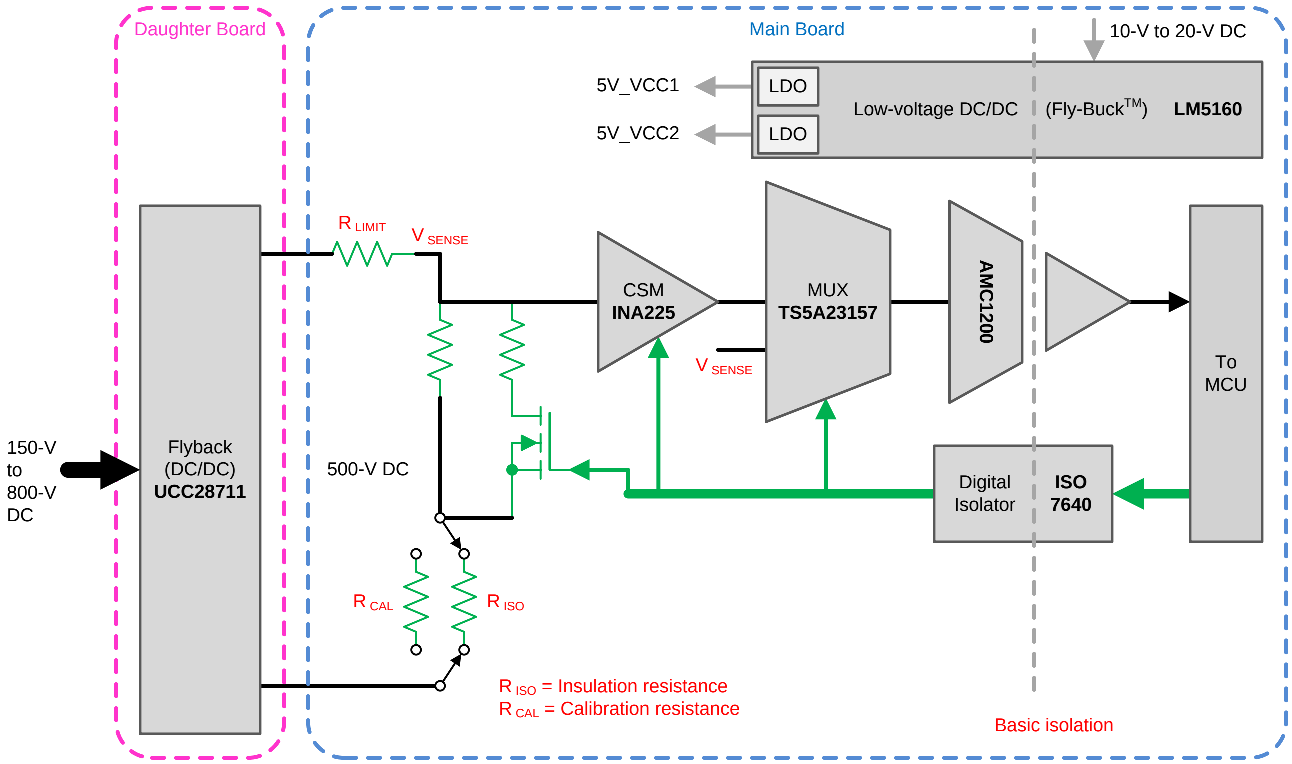


Figure 1. High-Level Block Diagram of Measurement Circuit

Figure 1 shows the high-level block diagram of the measurement circuit. As previously mentioned, this design consists of two boards: one main board (TIDA-00440MB) and one daughter board (TIDA-00440DB). The flyback (DC/DC) block on the left side of Figure 1 is the daughter board. All the remaining blocks are present on the main board.

The leakage current is measured by applying a fixed voltage and measuring the voltage across the shunt that is a result of the leakage current. The reference design uses different switchable shunt resistances, which are switched on in a sequence to measure the insulation resistance. When there is a dead short, the insulation resistance is 0 Ω and a full current (or maximum) can pass through the insulation resistance. At this point in the measurement having a smaller shunt value (by turning on all of the switches) is mandatory. In the other case, when the insulation is higher, a higher shunt value is required. The leakage current flowing through the shunt or shunts is measured using a current shunt monitor (INA225). The leakage current is amplified with different gains (if required), which can be programmed using pins GS0 and GS1 of the INA225 device. If using the gain of the INA225 is not required, the voltage across the shunt can be routed directly by using an onboard multiplexer (TS5A23157). The measured output voltage is isolated using an isolated amplifier (AMC1200), which has an output that can connect to an MCU. The switchable shunts and the multiplexer (MUX) channels are controlled through DIP switches, which are isolated using a digital isolator (ISO7640FM). The DIP switches are used to emulate the signals coming from the MCU to change the gain and shunts. The board operates from 15 V and then generates two isolated 5-V rails through the Fly-Buck. The primary side generates 3.3 V.

The daughter board consists of an isolated discontinuous mode (DCM) flyback circuit for generating 500-V DC from an input voltage ranging from 150-V DC to 800-V DC. On the main board, there is a provision to measure the 500-V DC output voltage for diagnostic purposes.

4.1 Highlighted Products

The TIDA-00440 reference design features the following devices, which were selected based on their specifications.

1. INA225 — Programmable gain, voltage output, and current shunt monitor
2. AMC1200 — Precision fully-differential isolation amplifier
3. LM5160 — Wide input, 1.5-A synchrounous Fly-Buck converter
4. UCC28711 — Constant-voltage, constant-current controller with primary-side regulation
5. CSD13202Q2 — 12-V, N-channel NexFET™ power MOSFETs
6. ISO7640FM — Low-power, quad-channel digital isolators
7. TS5A23157 — Dual 10-Ω SPDT analog switch
8. TLV1117-50 — 800-mA, 5-V fixed, low drop-out voltage regulator
9. LP2985A-50 — 150-mA, 5-V fixed, low drop-out voltage regulator
10. INA333 — Low power instrumentation amplifier

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 guide.

5 Principle of Operation

5.1 Current-Shunt Approach

This design uses a current-shunt approach to measure the insulation resistance. Figure 2 shows a schematic of the current-shunt approach. The circuit consists of three stages: the current shunt monitor, multiplexer, and isolation amplifier.

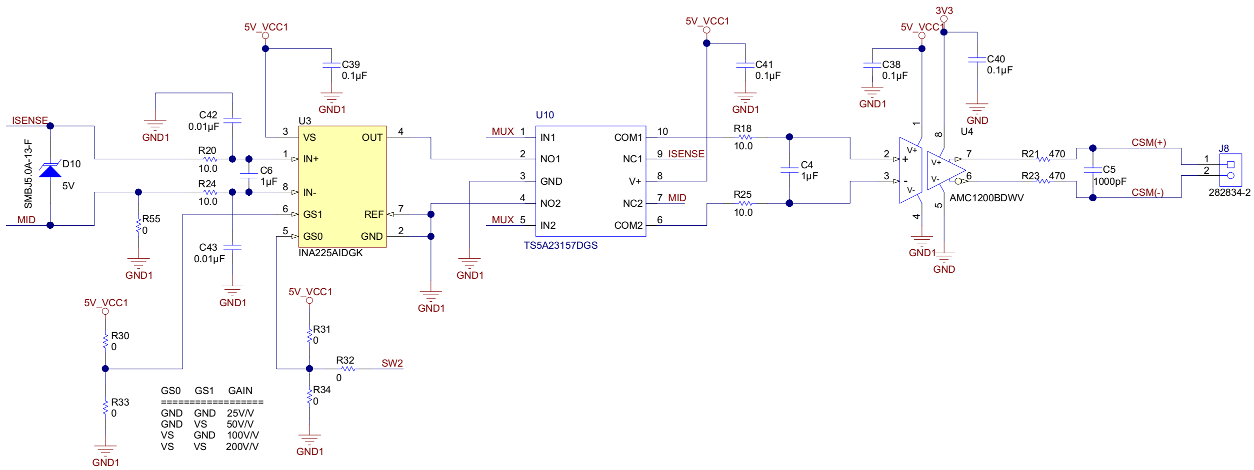


Figure 2. Signal Chain for Current Shunt Method

Multiple shunts are used in this design, which is important to note. Figure 3 shows the shunt resistors used for the insulation measurement. R13 is the fixed shunt and R11−R12 are switched on and off by using two MOSFETs (Q1 and Q2), respectively. Both of the MOSFETs are CSD13202Q2 logic-level NexFETs from TI.

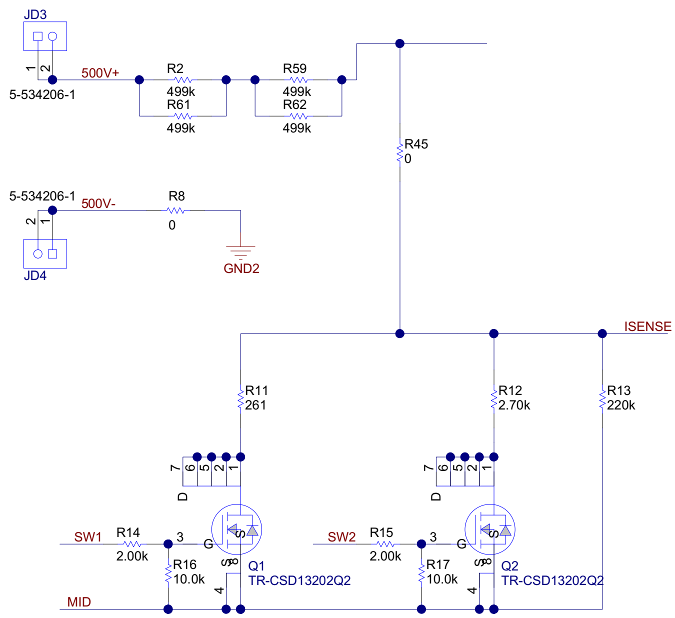


Figure 3. Schematic With Multiple Shunts

The current shunt monitor used in this design is INA225 (see Figure 4). The voltage across the shunt (between the ISENSE and MID points in the schematic) is connected to the inputs of INA225. The board has provisions to ensure protection, such as a 5-V clamp diode (D10) and differential caps (C42 and C43). These protections are currently not populated on the board and are marked as do not populate (DNP). The gain of INA225 is programmable and can be set by using the GS0 and GS1 pins. Table 2 shows the gain setting for INA225. The gain can also be programmed using a signal SW2 coming from the digital isolator.

Table 2. Gain Setting for INA225

GAIN	GS0	GS1
25 V/V	GND	GND
50 V/V	GND	VS
100 V/V	VS	GND
200 V/V	VS	VS

The TS5A23157 is an analog multiplexer with two differential channels. One channel is connected to the output of INA225 and the second channel is connected directly to the sense signal (between ISENSE and MID). The selection between the two differential channels of TS5A23157 is controlled by the signal MUX, coming from the digital isolator. During scenarios of high leakage current, gain may not be required and the INA225 monitor can be bypassed using the TS5A23157 device.

NOTE: When INA225 is not used for providing the gain, TI recommends to unpopulate R20 and R24 to prevent any effect due to the input impedance of INA225.

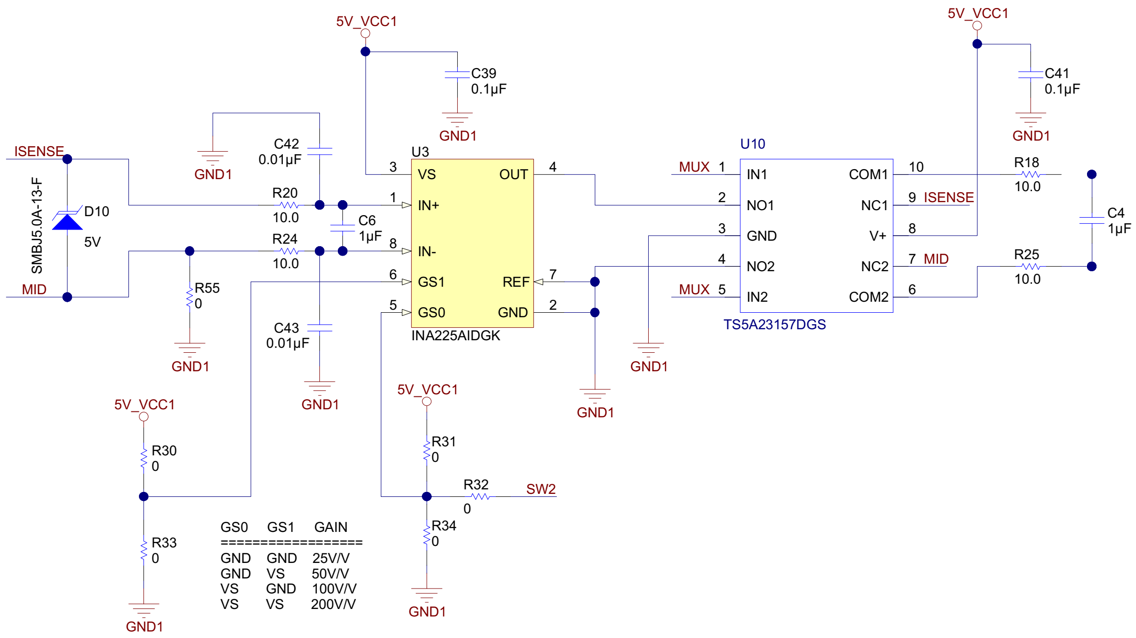


Figure 4. INA225 and TS5A23157 Section for Current Shunt Method

The output of TS5A23157 is connected to the isolated amplifier AMC1200 (see Figure 5). The non-isolated side of AMC1200 is powered with 5V_VCC1 coming from the TLV1117-50. The isolated side of AMC1200 is powered with 3.3 V coming from the LM5160 Fly-Buck power supply section. Both of the supplies are decoupled using 0.1-µF capacitors (C38 and C40 respectively). The differential output of AMC1200 is available on terminal J8.

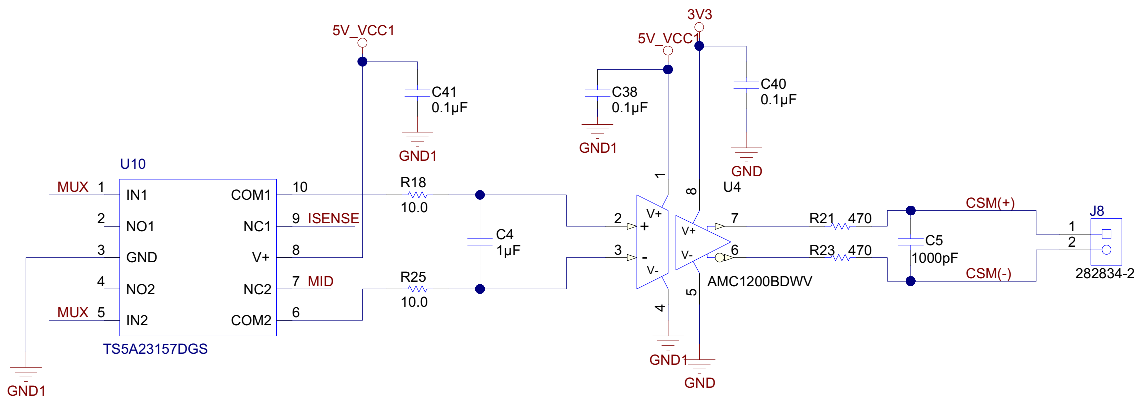


Figure 5. AMC1200 Section of Current Shunt Method

5.1.1 Single-Shunt Approach

In this approach, both the MOSFETs Q1 and Q2 are turned off using signals SW1 and SW2, respectively. So, the shunt resistor used in this case is R13 only (fixed at a value of 22 Ω). To cover the entire range of insulation resistance, the gain of INA225 is varied using GS0 and GS1 pins. Figure 6 shows the simplified connection diagram for this approach. Section 8.2 shows the measurement accuracy for this approach.

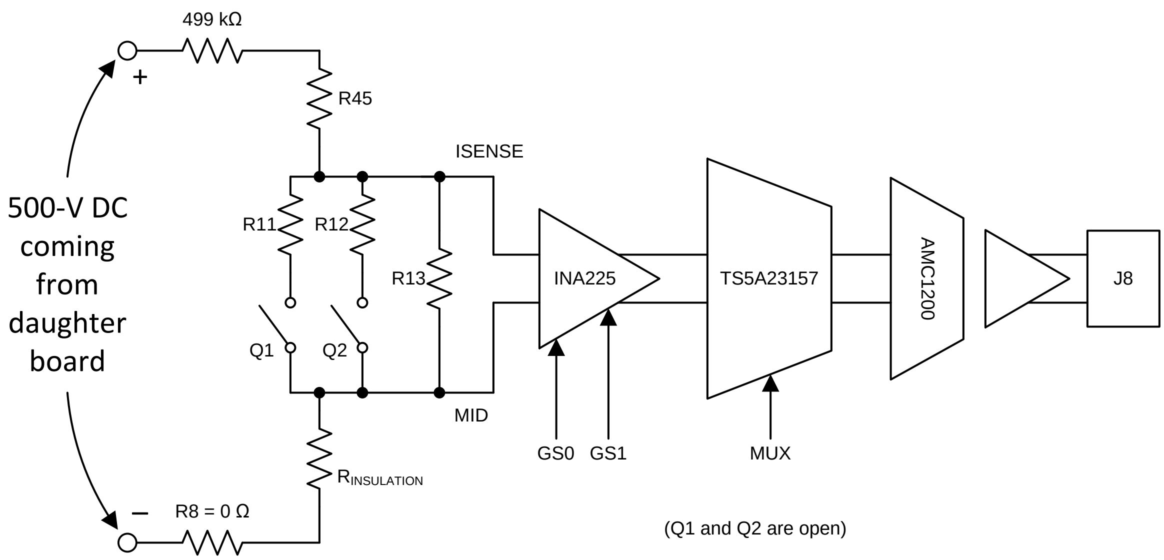


Figure 6. Simplified Connection Diagram for Single-Shunt Approach

5.1.2 Multiple-Shunt Approach

In this approach, MOSFETs Q1 and Q2 are turned on or off based on the output voltage measured on terminal J8. The total shunt resistance can be a combination of R11, R12, and R13. In this approach, INA225 is not used (so R20 and R24 must be unpopulated). Figure 7 shows the simplified connection diagram for this approach. Section 8.1 shows the measurement accuracy for this approach.

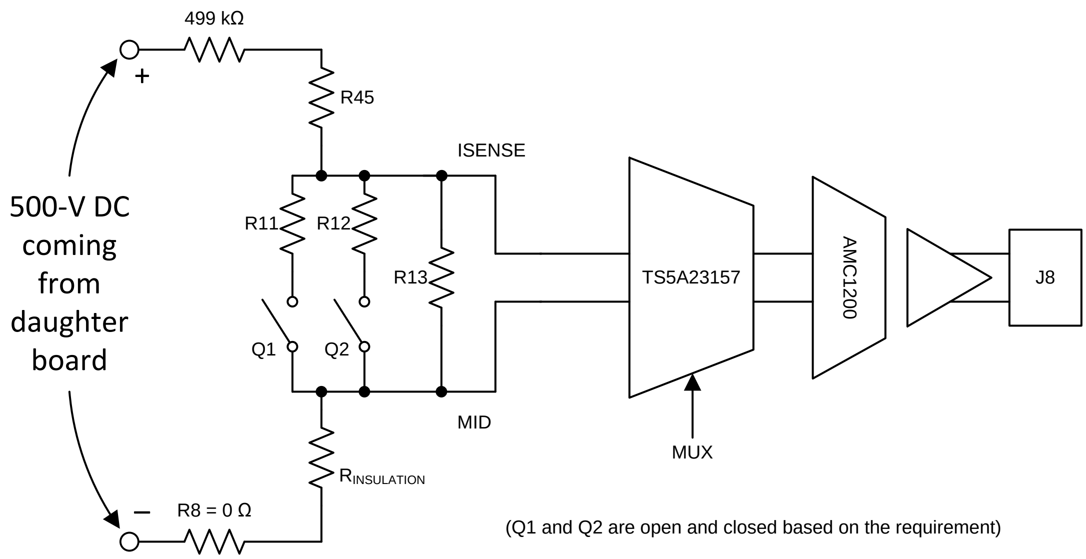


Figure 7. Simplified Connection Diagram for Multiple-Shunt Approach

5.2 Resistive Divider Approach

This design also uses the resistive divider approach to measure the insulation resistance. Figure 8 shows a schematic of the resistive divider approach.

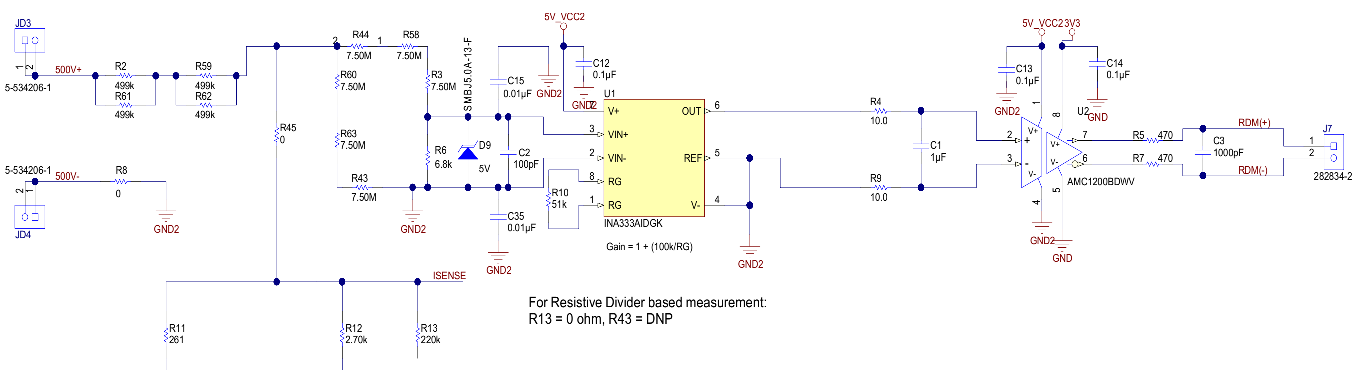
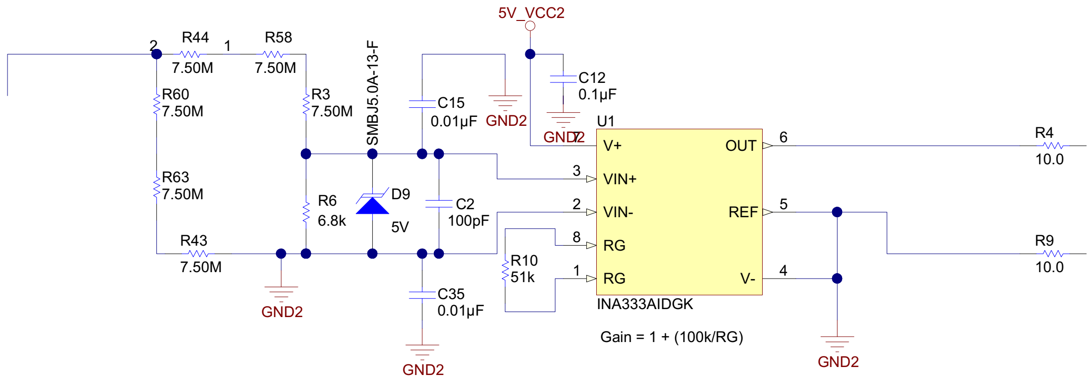


Figure 8. Signal Chain for Resistive Divider Method

The circuit consists of two stages: the instrumentation amplifier and an isolation amplifier. This reference design uses the instrumentation amplifier INA333 (see Figure 9).



For Resistive Divider based measurement:
R13 = 0 ohm, R43 = DNP

Figure 9. INA333 Section for Resistive Divider Method

The 500-V DC coming from the daughter board is applied across the insulation resistance. The voltage developed across the insulation resistance is divided by four resistors: R44, R58, R3, and R6. An important thing to note is that the total resistance is divided into three 7.5-MΩ resistors to reduce the voltage stress on each of the resistors. A single high-voltage resistor is costly in comparison to the three different low-voltage resistors. The voltage across R6 is fed to the input of the instrumentation amplifier INA333. One 100-pF capacitor (C2) is used as a filter for any noise present on the input signal. The board has provisions to ensure protection, such as a 5-V clamp diode (D9) and differential caps (C15 and C35). These protections are currently not populated on the board and are marked as DNP. The gain of the INA333 amplifier can be set by the RG pin (that is R10 in Figure 9) using the following formula:

$$\text{Gain} = 1 + (100\ \text{k} / R_G) \tag{1}$$

Currently the gain is set at unity because of the signal levels. The output of INA333 is connected to the isolated amplifier AMC1200 (see Figure 10).

NOTE: The primary reason for using an INA333 amplifier is to provide a high input impedance for the measurement circuit. For lower-cost applications, a simple op-amp based, non-inverting unity-gain buffer can be used.

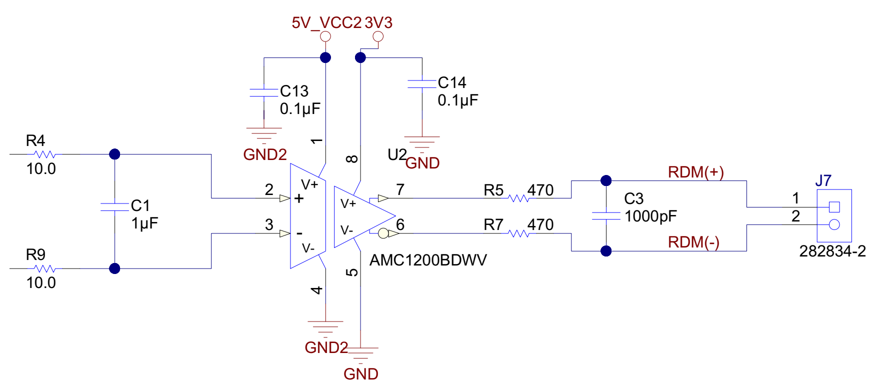


Figure 10. AMC1200 Section of Resistive Divider Method

The non-isolated side of the AMC1200 device is powered with 5V_VCC2 coming from the LP2985A-50. The isolated side of the AMC1200 device is powered with 3.3 V coming from the LM5160 Fly-Buck section. Both of the supplies are decoupled using 0.1-µF capacitors (C13 and C14, respectively). The differential output of the AMC1200 is available on terminal J7.

Figure 11 shows a simplified circuit for the resistive divider approach.

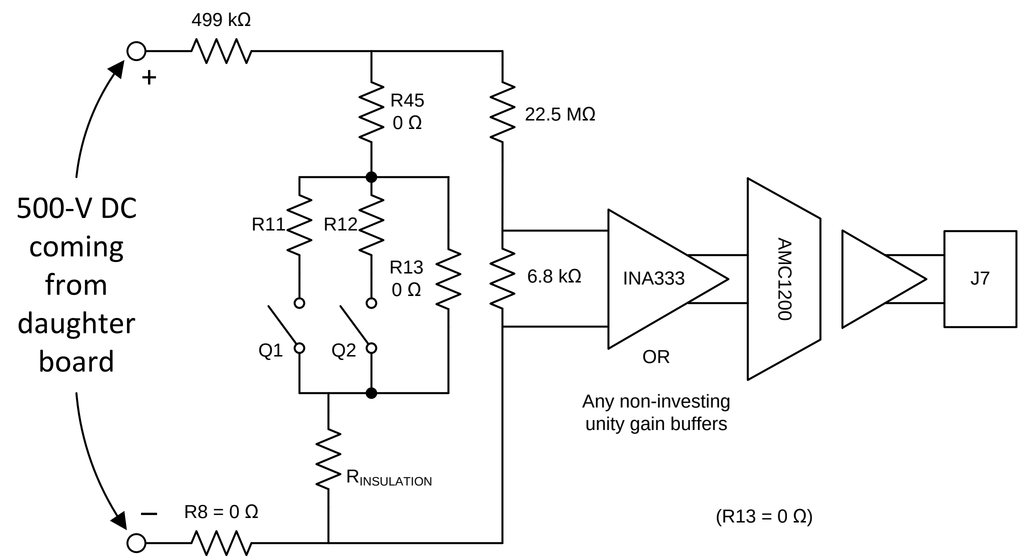


Figure 11. Simplified Resistive Divider Approach

Figure 12 shows the TINA-TI™ simulation software for the resistive divider approach. The graph from the TINA-TI simulation (Figure 13) shows that, due to the ratio of resistors, the voltage across R6 does not vary linearly with the insulation resistance. The measured value of voltage at the output of AMC1200 is almost saturated with an insulation resistance value greater than 15 MΩ. Section 8.3 shows the same observation during the testing and in the results.

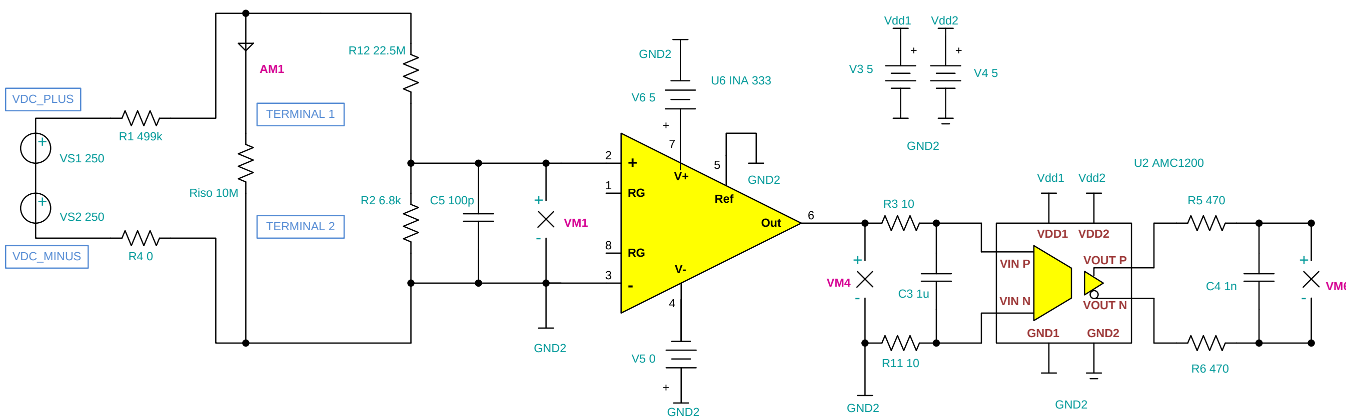


Figure 12. TINA-TI Simulation for Resistive Divider Approach

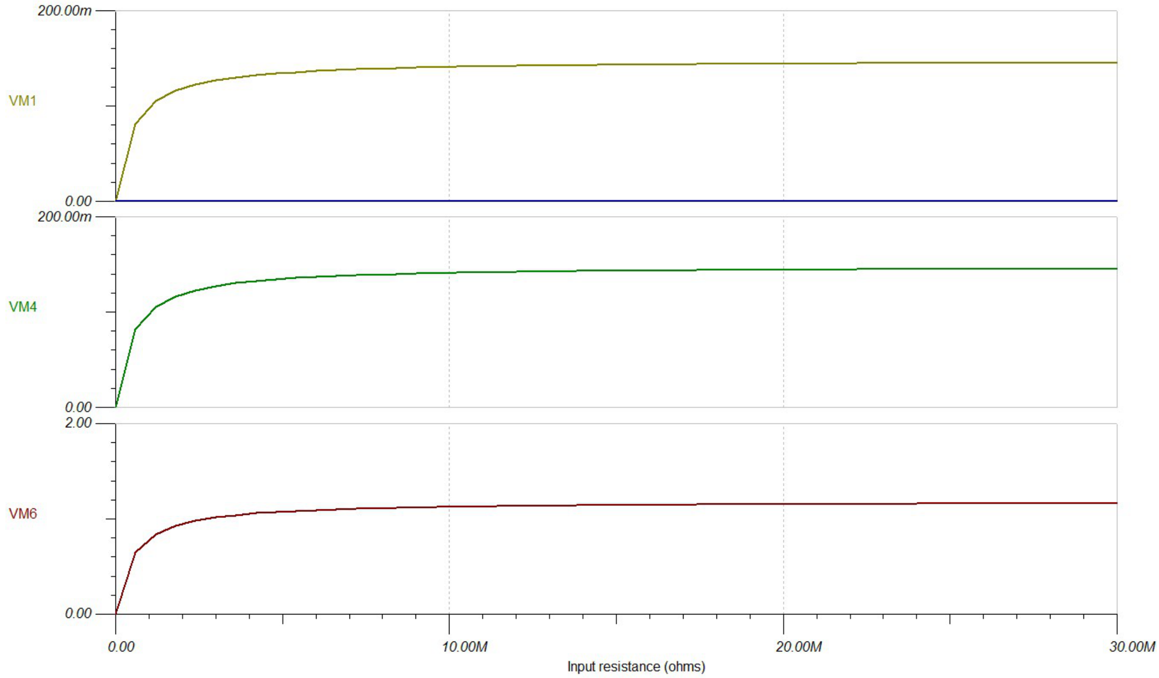


Figure 13. TINA-TI Graphs Showing Saturation

Though the resistive divider approach is investigated in this design, it is not useful as an approach to cover the entire range for insulation resistance up to 100 MΩ.

6 Circuit Design

6.1 Sensing of 500-V DC for Resistive Divider Approach

To measure the 500-V DC voltage, the design is provided with an isolated amplifier AMC1200. Figure 14 shows a schematic of the AMC1200.

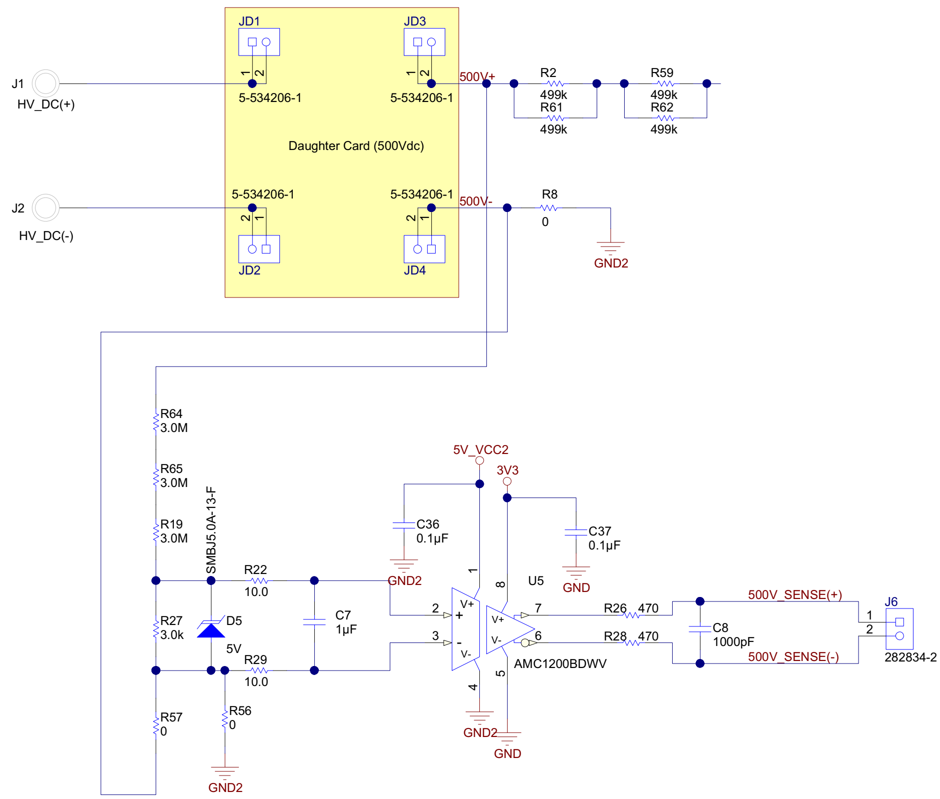


Figure 14. Sensing of 500-V DC Voltage

The 500-V input coming from the daughter card is stepped down using four resistors: R64, R65, R19, and R27. The voltage across R27 is taken as an input to the AMC1200. An important thing to note is that the total resistance is divided into three 3-MΩ resistors to reduce the voltage stress on each of the resistors. One single high-voltage resistor is costly in comparison to the three different low-voltage resistors. The board has a 5-V clamp diode (D5) if protection is required. This protection is currently not populated on the board and is marked as DNP. The non-isolated side of the AMC1200 is powered with 5V_VCC2 coming from the LP2985A-50. The isolated side of the AMC1200 is powered with 3.3 V coming from the LM5160 Fly-Buck section. Both the supplies are decoupled using 0.1-µF capacitors (C36 and C37, respectively). The differential output of the AMC1200 is available on terminal J6.

An important thing to note is that the input impedance of the AMC1200 amplifier is approximately 28 kΩ (typical). With such a high value for the sense resistor (R27 = 3 kΩ), the effect of input impedance must be considered. The current passing through each of the resistors must also be very low to reduce the overall power consumption. In short, this trade-off must be addressed.

6.2 Digital Isolator and DIP Switches

As previously mentioned, signals SW1 and SW2 control the MOSFETs in the current shunt method. The MUX signal is used to select the input channel of the multiplexer TS5A23157. The signal RELAY controls the onboard relay. The intention of this design is to have all of these signals originate from an MCU in the end-application. To emulate this intention, the design uses four-channel DIP switches (see Figure 15). Because the MCU operates at 3.3 V and the control signals control the high-voltage circuits, isolating the MCU and high-voltage circuit is important. The ISO7640FM is a digital isolator from TI with four channels. The outputs are enabled when EN = 1. To enable and disable the outputs of the ISO7640FM, two resistors are used (R41 and R42). R41 is currently populated, which means that the outputs are enabled. The isolated side of the ISO7640FM device is powered with 5V_VCC1 coming from the TLV1117-50; the non-isolated side is powered with 3.3 V coming from the LM5160 Fly-Buck section. Both of the supplies are decoupled using 0.1-µF capacitors (C9 and C10, respectively).

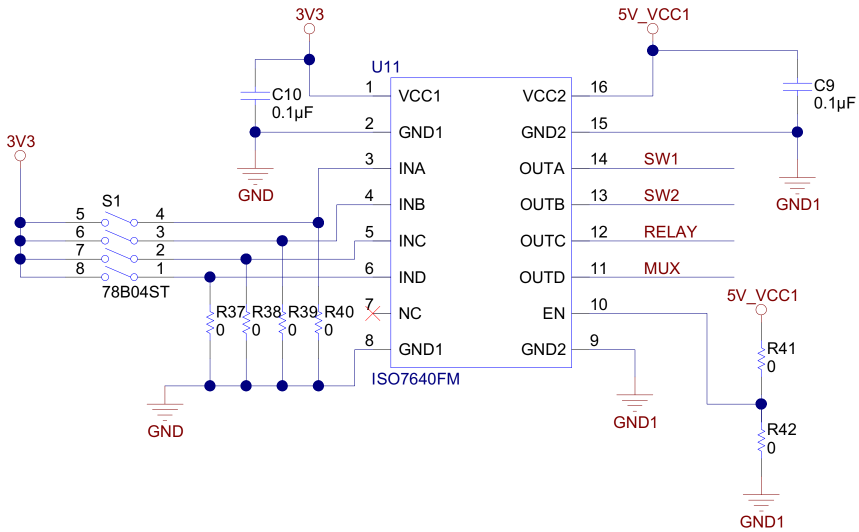


Figure 15. ISO7640FM With DIP Switches

6.3 Onboard Relay

As Figure 16 shows, the TIDA-00440 reference design uses one relay for connecting and disconnecting the end equipment from the measurement circuit. The normally closed (NC) contacts of the relay are connected to a calibration resistor R35. Banana terminals J3 and J4 are used for connecting the end equipment that requires insulation measurements. The relay is driven using a simple BJT, which is controlled by the signal RELAY originating from the digital isolator IS07640FM. Because the application requires a high voltage of 500 V, selecting the relay with the proper creepage and clearances is important.

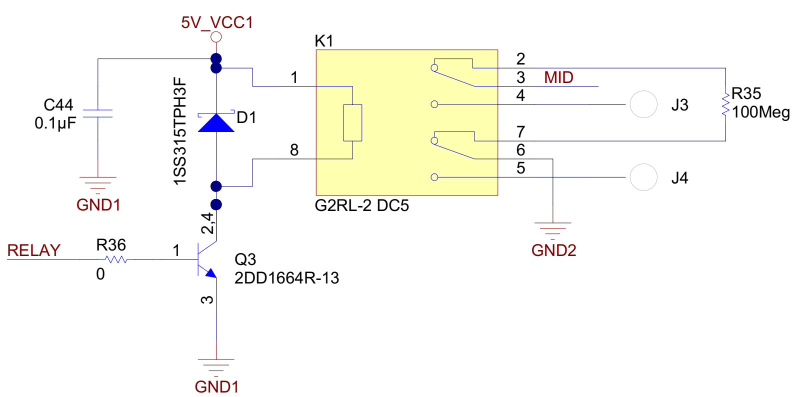


Figure 16. Relay for On-the-Fly Connection of Insulation Resistance to Measurement Circuit

6.4 Calculation of Power Consumption for All Components

Figure 17 shows the scheme for the power supply. The operating input voltage range for the Fly-Buck power supply is 10-V DC to 20-V DC. The 3.3 V (required to power the non-isolated side) generates from the primary winding of the Fly-Buck. Two +6-V outputs generated from the Fly-Buck transformer are converted to +5-V outputs, each using two different LDOs. The +5V_VCC1 is used to power the measurement circuit for the current-shunt approach and the relay. The +5V_VCC2 is used to power the measurement circuit for the resistive divider approach.

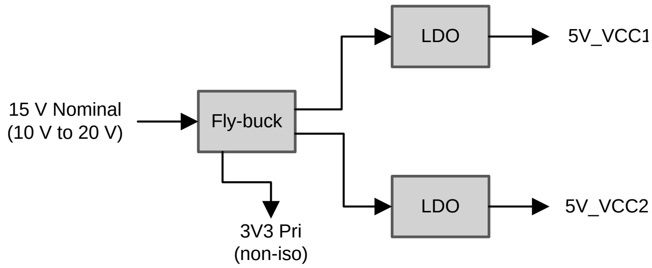


Figure 17. Scheme for Power Supply Section

Table 3 shows the total power consumption calculation for the design.

Table 3. Calculation of Power for Each Onboard Device

SR. NO.	NAME OF THE IC	POWER SUPPLY USED	MAX CURRENT TAKEN BY IC (IN A)	SUPPLY VOLTAGE (IN V)	POWER CONSUMPTION (IN W)	TOTAL OUTPUT CURRENT (IN A)	SELECTED LDO SHOULD HAVE OUTPUT CURRENT OF
1	INA333	5V_VCC(2)	0.01	5	0.05	0.14	0.15
2	AMC1200 (resistive divider approach) primary	5V_VCC(2)	0.065	5	0.325		
3	AMC1200 (500-V DC sensing) primary	5V_VCC(2)	0.065	5	0.325		
4	INA225	5V_VCC(1)	0.03	5	0.15	0.23749	0.25
5	AMC1200 (current shunt approach) primary	5V_VCC(1)	0.065	5	0.325		
6	TS5A23157	5V_VCC(1)	0.02	5	0.1		
7	ISO7640FM secondary	5V_VCC(1)	0.04249	5	0.21245		
8	Relay	5V_VCC(1)	0.08	5	0.4		
9	AMC1200 (resistive divider approach) secondary	3V3_Pri (non-iso)	0.06	3.3	0.198	0.02103717	0.2
10	AMC1200 (current shunt approach) secondary	3V3_Pri (non-iso)	0.06	3.3	0.198		
11	AMC1200 (500-V DC sensing) secondary	3V3_Pri (non-iso)	0.06	3.3	0.198		
12	ISO7640FM primary	3V3_Pri (non-iso)	0.0063749	3.3	0.02103717		

For the calculation of individual devices, refer to the specific datasheet. Table 4 shows the selection of LDOs, which is based on the output currents and the power levels required.

Table 4. Final Selection of LDOs

LDO SELECTION					
POWER SUPPLY NAME ON BOARD	INPUT VOLTAGE	OUTPUT VOLTAGE	OUTPUT CURRENT	PART NUMBER	PACKAGE
5V_VCC(1)	6	5	0.25	TLV1117-50	8 SON
5V_VCC(2)	6	5	0.15	LP2985A-50	SOT-23
3V3	15 (20 V max)	3.3	3.3	–	–

6.5 Design of Fly-Buck Power Supply Using LM5160

The primary goal of this design is to provide a high-performance, cost-effective, and easy-to-design isolated power supply solution. The Fly-Buck is basically a buck regulator with couple windings added to the inductor. The coupled windings can generate isolated outputs. View more details about this topology in Appendix A—Fly-Buck Power Supply.

6.5.1 Setting the Primary Side Output Voltage

The primary-side regulation (PSR) of the Fly-Buck topology is realized through the coupled winding of the transformer, as the primary output clamps the secondary outputs during the duty-off time. Setting the primary output is the first step in a Fly-Buck converter design. Having the duty cycle below 50% is optimal because the Fly-Buck secondary outputs transfer the energy in off-time; and having a duty cycle too high affects the energy flow. Based on $V_{PRI} = D \times V_{IN}$, the primary side output is initially set at 3.3 V, which gives 33% of D at the minimum of V_{IN} = 10 V. Then the secondary-to-primary turns ratio of the transformer can be estimated as $N = V_{SEC} / V_{PRI}$ = 1.91, and the primary-side average current at full-load is roughly $i_{opri} + 2(N \times i_{osec})$ = 1.155 A, accounting for a 250-mA current on each of the secondary outputs. These parameters must be tuned and adjusted during the design process. In the final design, the primary output voltage is settled at 3.3 V, as Figure 18 shows.

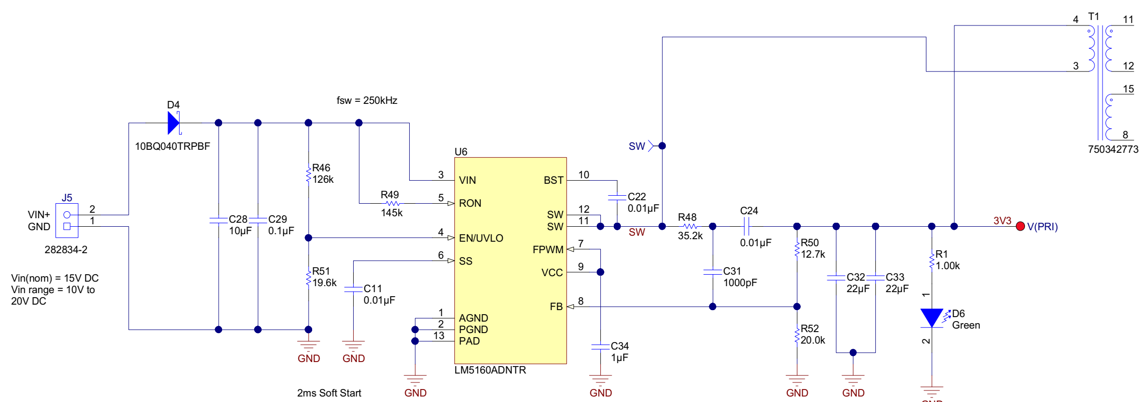


Figure 18. Primary Section of Fly-Buck Using LM5160

6.5.2 Transformer Design

The desirable transformer turns ratio is calculated based on the secondary-to-primary output ratio, which is 1.91:1. The rectifier diode forward voltage and winding data capture record (DCR) drop must be taken into account. The turns-ratio also has a certain granularity limit subject to the actual winding turn count. To accommodate that granularity limit, adjust the primary output voltage accordingly.

The primary side inductance determines the current ripple in the transformer. The LM5160 device limits the peak current to approximately 2.1 A, and from the estimated 1.155-A average current level, there is plenty of ripple margin.

The transformer used in this design is built with an EPW15-core through-hole package by Wurth Elektronik and the part number is 750342773. The transformer specification has a secondary-to-primary turns ratio of 1.91:1, and both the secondary windings have the same turn count. The primary inductance is 60 µH. Figure 19 shows the symbol for this transformer. The following list shows the isolation levels:

1. Between primary and secondary: Creepage (9.2 mm) and clearance (8 mm)
2. Between primary and secondary: 1.5-kV AC, one-minute isolation (dielectric rating) between primary and secondary
3. Isolation between primary and secondary pass: 7.4 kV impulse test voltage (1.2/50 µsec)
4. Isolation between two secondaries: Clearance (5.5 mm) and type test = 1.8 kV_{RMS}

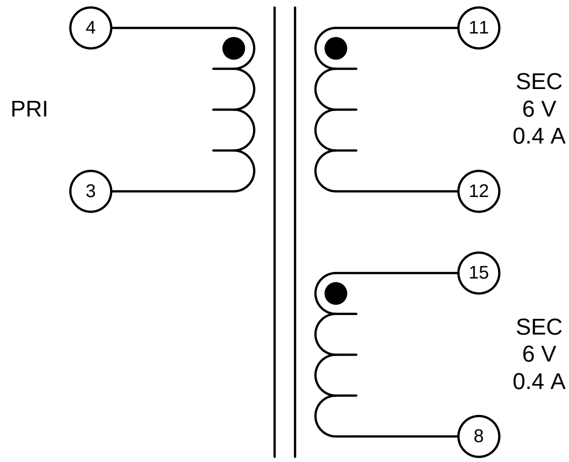


Figure 19. Fly-Buck Transformer Symbol

6.5.3 Shutdown Function

The LM5160 has an undervoltage lock out (UVLO) pin for the low voltage shutdown, which can be utilized as an enable function pin. External circuitry can be used to pull the UVLO pin to ground to shut down the operation of the power supply.

6.5.4 Generating the Output Voltages

The total output voltage from the secondary winding is 6 V on each winding. Figure 20 shows the secondary section of the schematic.

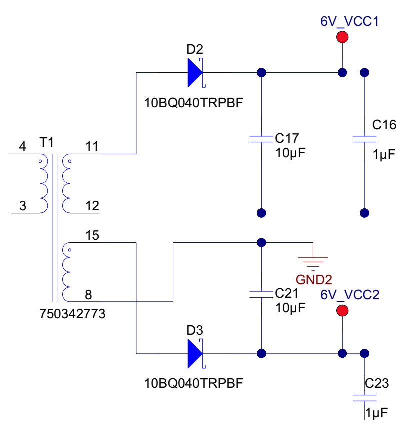


Figure 20. Secondary Section of Fly-Buck Using LM5160

6.6 Generating 5V_VCC1 and 5V_VCC2

Each of the rails from the two isolated, 6-V rails (generated from the LM5160 Fly-Buck section) are converted to 5 V by using two fixed output linear regulators TLV1117-50 and LP2985A-50.

The TLV1117-50 is a fixed, 5-V output, LDO regulator designed to provide up to 800 mA of output current. A 0.1-uF cap and a 1-uF cap are connected on both the input as well as the output sides of the LDO. The light-emitting diode (LED) D7 indicates when the +5V_VCC1 is available. Figure 21 shows the schematic capture for the TLV1117-50 section.

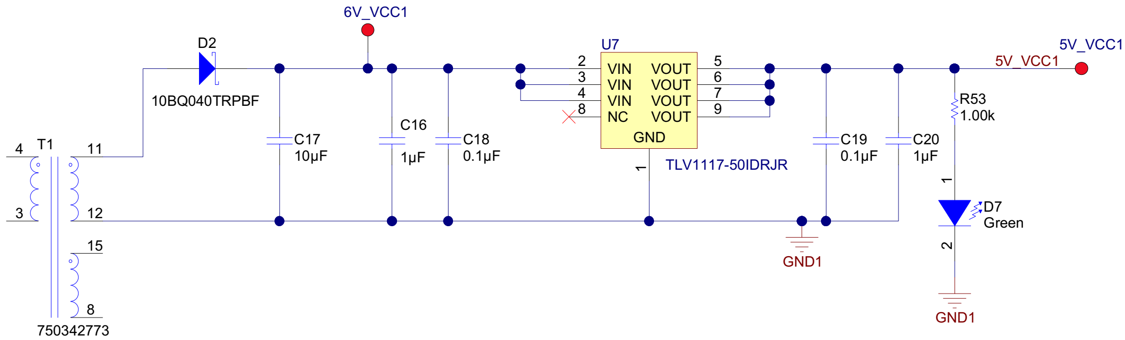


Figure 21. TLV1117-50 for 5V_VCC1

LP2985A-50 is a fixed 5-V output, LDO regulator designed to provide up to 150 mA of output current. A 0.1-uF cap and a 1-uF cap are connected on both the input as well as the output sides of the LDO. The D8 LED indicates when the +5V_VCC2 is available. Figure 22 shows the schematic capture for the LP2985A-50 section.

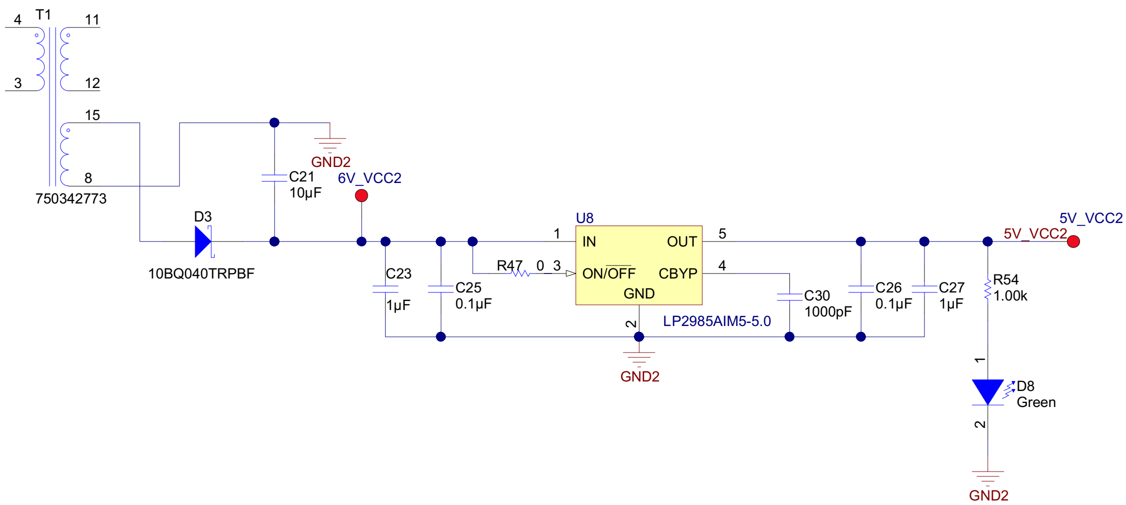


Figure 22. LP2985A-50 for 5V_VCC2

6.7 Design of Flyback Power Supply Using UCC28711 (TIDA-00440DB Daughter Board)

6.7.1 Requirements of the Power Supply

The requirements of the main isolated power supply to be used in insulation measurement are as follows:

1. Input range: 150-V DC to 800-V DC
2. Output voltage: 500-V DC
3. Output current: 2 mA (max)
4. < 1% output ripple voltage
5. Isolation: Functional
6. Regulation: < 5%
7. Size: As compact as possible
8. Controller must be able to shut down the power supply when a measurement is not made

6.7.2 Circuit Design

To translate the Section 6.7.1 *Requirements of Power Supply* to the sub-system level, Section 6.7.2.1 through Section 6.7.2.3 lists the requirements of the PWM controller, MOSFETs, and transformer.

6.7.2.1 PWM Controller

Because a ±5% regulation is acceptable, a PSR controller is feasible for this task. The primary-side feedback eliminates the requirement of using optocoupler feedback circuits. A device with discontinuous conduction mode with valley switching can minimize switching losses. The UCC28711 is a suitable controller for this application. The UCC28711 device is a flyback power-supply controller, which provides accurate voltage and constant current regulation with primary-side feedback. The modulation scheme is a combination of frequency and primary peak-current modulation to provide high conversion efficiency across the load range. The controller has a maximum switching frequency of 106 kHz and allows for a shut-down operation using the NTC pin.

6.7.2.2 Transformer Design

The transformer design has the following specifications:

1. Input: 100-V DC to 850-V DC
2. Frequency: 70 kHz (min)
3. Ambient temperature: 60°C (max)
4. Output: Split into two secondaries – each of 250-V DC at 25 mA
5. Max. operating duration: 30 min
6. Topology: Flyback (DCM)
7. Controller to be used: UCC28711
8. Preferred core size: EE16 (EE16 core is required due to winding accommodation)
9. Insulation: Functional
10. Auxiliary winding: 15 V at 30 mA

Figure 23 shows the symbol for this transformer. The transformer used in this design is built with a EE16-core through-hole package by Wurth Elektronik, and the part number is 750342792. The transformer specification has a secondary-to-primary turns ratio of 2.88:1, and both the secondary windings have the same turn count. The secondary-to-auxiliary turns ratio is 15.76:1. The primary inductance is 736 μH.

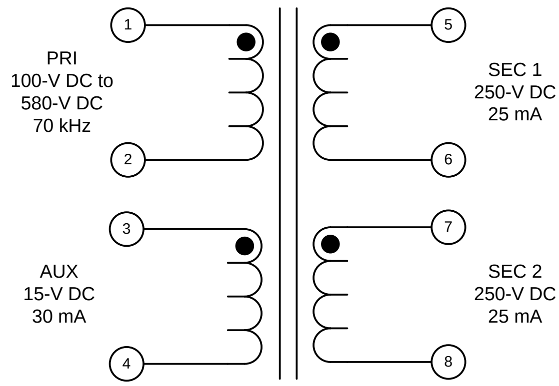


Figure 23. Fly-Buck Transformer Symbol

6.7.2.3 Power MOSFET

The power MOSFET must have a rated drain to source voltage VDS ≥ 1100 V to support an 800-V DC input and the power MOSFET must also support a 0.25-A (minimum) drain current. This reference design uses the IXTA06N120P, which is a 1200-V device with a drain current of 0.6 A.

6.7.2.4 Primary-Side Regulation

In primary-side control, the output voltage is sensed on the auxiliary winding during the transfer of transformer energy to the secondary. Appendix B—PSR Flyback Power Supply provides more details on the component selection.

Figure 24 shows the schematic section of the primary feedback.

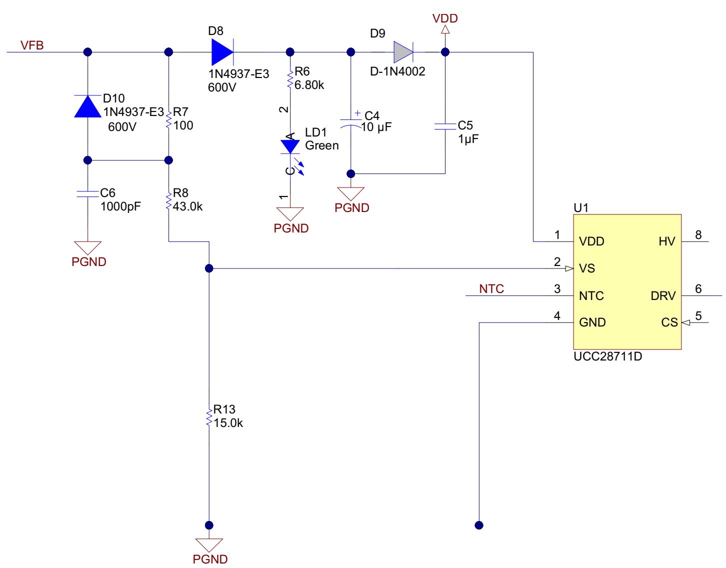


Figure 24. Primary Feedback

The output overvoltage function is determined by the voltage feedback on the VS pin. If the voltage sample on VS exceeds 115% of the nominal V_{OUT}, the device stops switching and also stops the internal current consumption of I_{FAULT}. Stopping the internal current consumption of I_{FAULT} discharges the VDD capacitor to the UVLO turn-off threshold. After this discharge, the device returns to the start state and a start-up sequence ensues.

Protection is included in the event of component failures on the VS pin. If complete loss of feedback information on the VS pin occurs, the controller stops switching and restarts.

6.7.2.5 Current Sensing

For this reference design, a 0.75-Ω resistor is selected based on a nominal maximum current-sense signal of 0.75 V. Figure 25 shows the current sense circuit of the schematic.

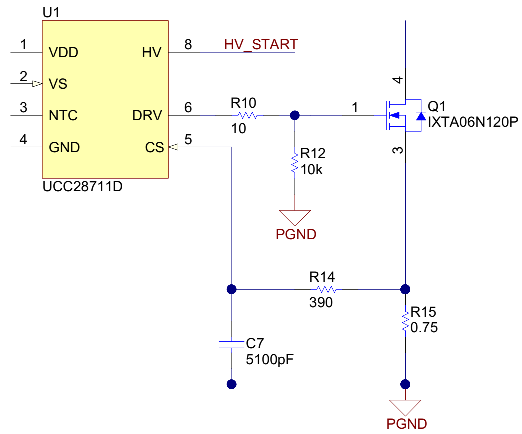


Figure 25. Current Sense

6.7.2.6 Power-On and HV Start-Up

Figure 26 shows the power-on sequence for the UCC28711 device. When the VDD pin of the UCC28711 reaches the V_{VDD_ON} threshold, the device generates three initial drive pulses for the MOSFET. These drive pulses turn on the PWM controller with the help of a high-voltage startup (HV) pin.

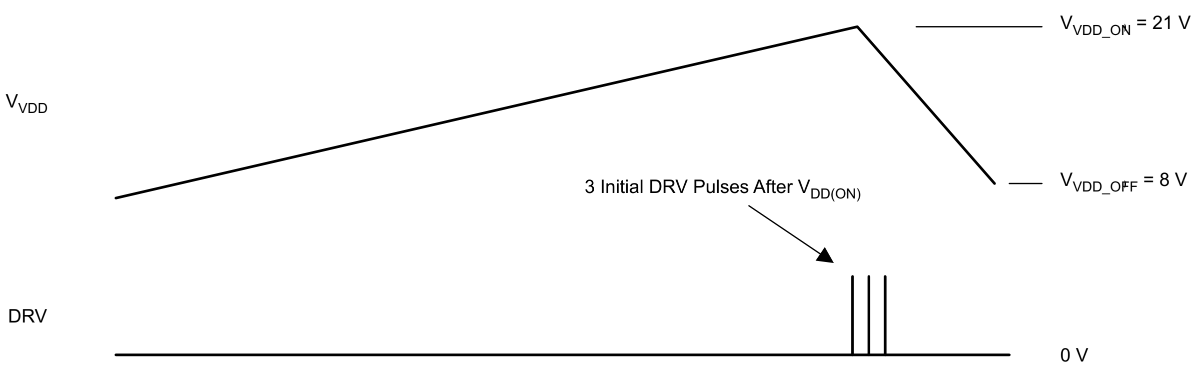


Figure 26. Power-On Sequence

The UCC28711 device has an internal 700-V startup switch. Because the DC bus can be as high as 800-V DC, an external Zener voltage regulator is used to limit the voltage at the HV pin to about 550-V DC. The typical startup current is approximately 300 µA, which provides fast charging of the VDD capacitor. The internal HV startup device is active until VDD exceeds the turn-on UVLO threshold of 21 V, at which time the HV startup device is turned off. In the off state, the leakage current is very low to minimize standby losses of the controller. When the VDD falls below the 8.1-V UVLO turn-off threshold, the HV startup device is turned on. Figure 27 shows the HV startup circuit.

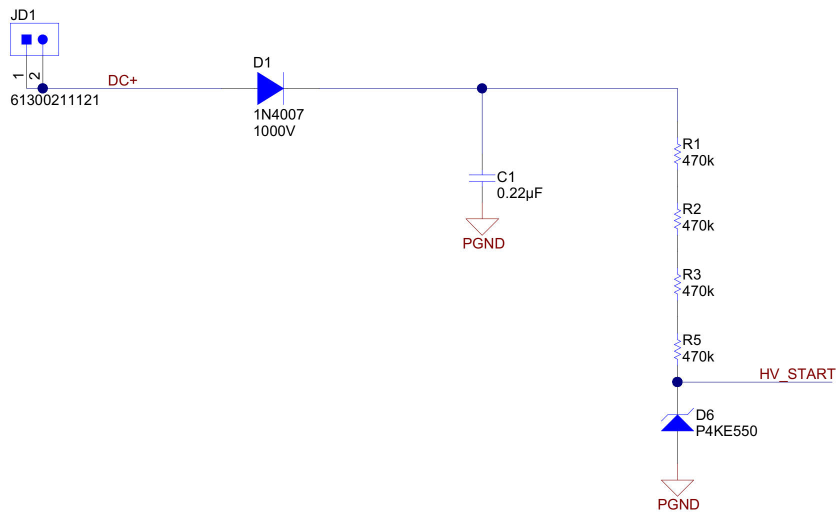


Figure 27. HV Startup

6.7.2.7 MOSFET Gate Drive

The DRV pin of the UCC28711 device is connected to the MOSFET gate pin through a series resistor. The gate driver provides a gate drive signal limited to 14 V. The turnon characteristic of the driver is a 25-mA current source, which limits the turnon dv/dt of the MOSFET drain. This characteristic reduces the leading-edge current spike, but still provides a gate drive current to overcome the Miller plateau. The gate-drive turnoff current is determined by the low-side driver R_{DS_ON} and any external gate-drive resistance. Figure 28 shows the gate drive for MOSFET.

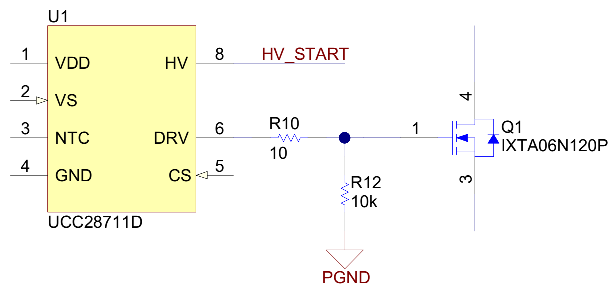


Figure 28. MOSFET Gate Drive

6.7.2.8 Shutdown Mechanism for UCC28711

The NTC pin of the UCC28711 device can be pulled down to shut down the PWM operation of the device. Figure 29 shows the isolated shutdown mechanism for the UCC28711 using an optocoupler. In situations that do not require measuring the insulation resistance, use a SHUTDOWN signal coming from any available MCU in the application to shut off the 500-V DC output.

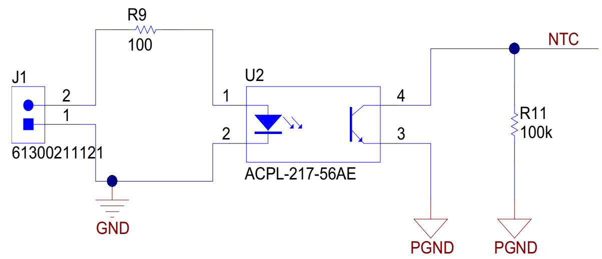


Figure 29. Isolated Shutdown for UCC28711

6.7.2.9 Generating Isolated 500-V DC Output

The two secondary windings of the transformer produce 250 V each while regulating. To generate 500 V, use a simple voltage doubler, as Figure 30 shows. In the case of a no-load condition, or during any abnormal condition, if the output tries to go much higher, a 550-V Zener (connected across the output) protects the output from going out of regulation.

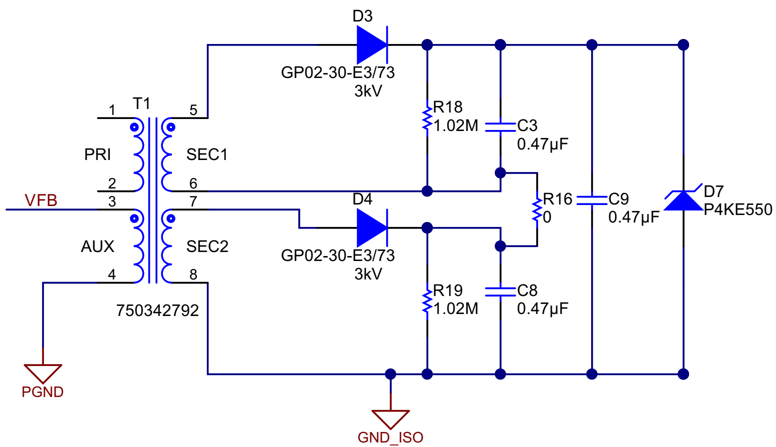


Figure 30. Generation of 500-V Output Using Voltage Doubler

7 Applications

Insulation measurement is important for a number of applications. Some of the applications include transformers, solar inverters, industrial motor drives (variable speed AC/DC drives, servo drives), and so forth. Figure 31 and Figure 32 show two of these applications.

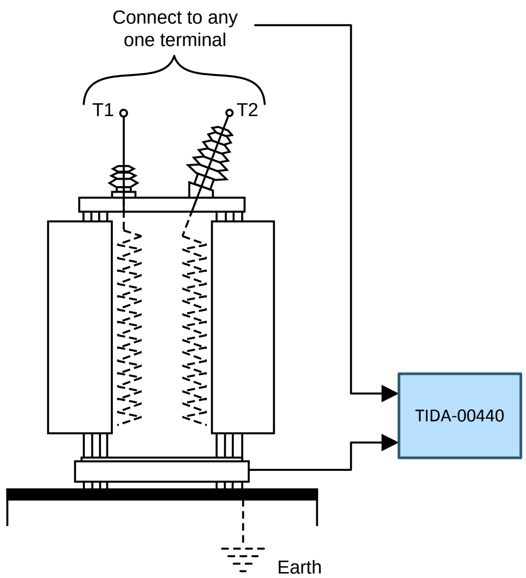


Figure 31. Measurement of Insulation Resistance for HV Transformer

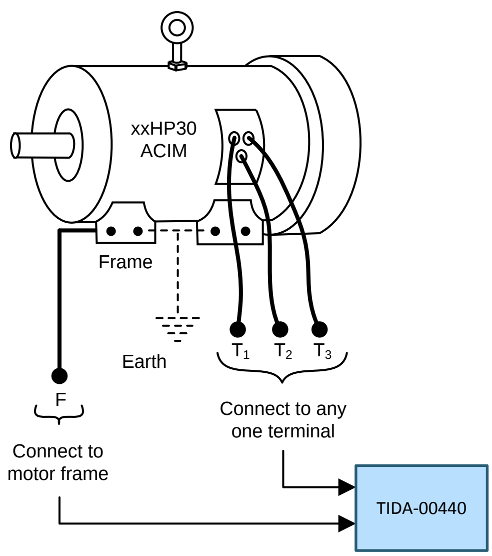


Figure 32. Measurement of Insulation Resistance for Motor

8 Test Data

The design is tested in all three configurations as explained in the following Section 8.1 through Section 8.3.

8.1 Multiple-Shunt Approach

As Section 5.1.2 explains, based on the insulation resistance, different shunt resistor values may be required. To implement this change, resistors R11, R12, and R13 are switched using MOSFETs Q1 and Q2. Figure 33 shows the measurement accuracy for this approach.

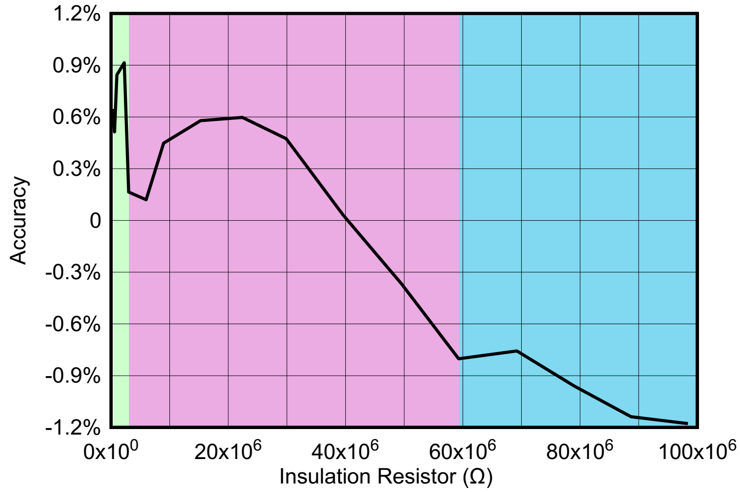


Figure 33. Accuracy for Multiple Switchable Shunt Approach

As Table 5 shows, the shunt resistor value changes on-the-fly (using SW1 and SW2 signals), while the output of the AMC1200 must not go below 200 mV at any time.

1. For an insulation resistance between 0 Ω and 3 MΩ, the value of shunt resistor is 220 kΩ || 2.7 kΩ || 261 Ω || 28.02 kΩ.
2. For an insulation resistance between 3.1 MΩ and 39.6 MΩ, the value of shunt resistor is 220 kΩ || 2.7kΩ || 28.02 kΩ.
3. For an insulation resistance between 39.7 MΩ and 98.4 MΩ, the value of shunt resistor is 220 kΩ || 28.02 kΩ.

The accuracy graph in Figure 33 highlights the three options using different colors.

One important point to note here is the 28.02-kΩ resistance in parallel with each of the combinations, which is the input impedance of the AMC1200 device. The accuracy numbers are calibrated and account for the change in input impedance of the AMC1200.

Table 5. Accuracy and Measurement Table for Multiple-Shunt Approach[(1)]

INSULATION RESISTOR (IN MΩ)	% ACCURACY (UNCALIBRATED)		MEASURED OUTPUT W/O INA		VALUE OF SHUNT RESISTOR
0.00E+00	0.41%		1.9014		220 kΩ || 2.7 kΩ || 261 Ω || 28.02 kΩ
9.98E+03	0.41%		1.8642		
9.97E+04	0.70%		1.5844		
6.00E+05	0.51%		0.86354		
9.89E+05	0.84%		0.63813		
2.25E+06	0.91%		0.346		
3.00E+06	0.16%		0.27282		
5.99E+06	0.12%		1.489		220 kΩ || 2.7 kΩ || 28.02 kΩ
8.97E+06	0.45%		1.02242		
1.53E+07	0.58%		0.6148		
2.24E+07	0.60%		0.42361		
2.99E+07	0.47%		0.31913		
3.96E+07	0.03%		0.24146		
4.96E+07	–10.07%	–0.37% (calibrated)	1.9842	1.8169 (calibrated)	220 kΩ || 25.75 kΩ
5.93E+07	–10.24%	–0.80% (calibrated)	1.6618	1.5159 (calibrated)	
6.92E+07	–9.99%	–0.76% (calibrated)	1.4254	1.3006 (calibrated)	
7.90E+07	–10.02%	–0.96% (calibrated)	1.2496	1.138 (calibrated)	
8.87E+07	–10.08%	–1.14% (calibrated)	1.1142	1.01292 (calibrated)	
9.84E+07	–9.23%	–1.18% (calibrated)	1.0049	0.9122 (calibrated)	

(1) The accuracy numbers are calibrated and take care of the change in input impedance of the AMC1200.

8.2 Single-Shunt Approach

As Section 5.1.1 explains, the circuit can also be tested with a single shunt resistor. Figure 34 shows the accuracy results for a single-shunt approach.

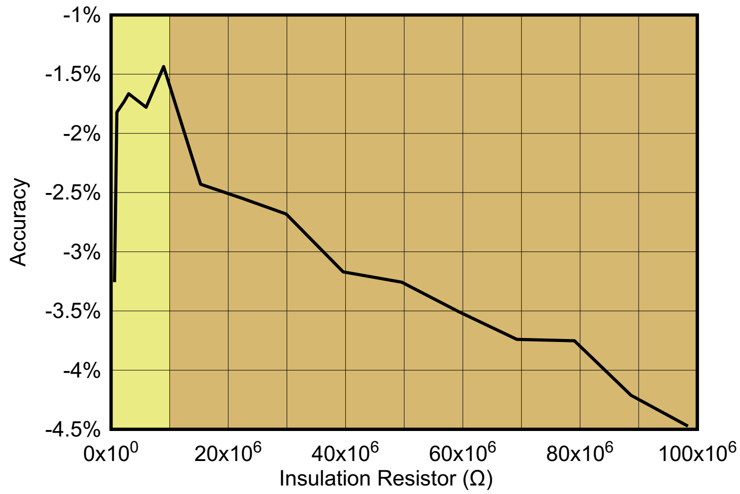


Figure 34. Accuracy for Single-Shunt Approach

As Table 6 shows, the shunt resistor value is fixed at 22 Ω. In this method, the gain of INA225 varies on-the-fly. The accuracy graph in Figure 34 shows both of the gain settings highlighted with different colors.

Table 6. Accuracy and Measurement Table for Single-Shunt Approach

INSULATION RESISTOR (IN MΩ)	% ACCURACY (UNCALIBRATED)	MEASURED O/UTPUT W/O INA	VALUE OF SHUNT RESISTOR
6.00E+05	–3.26%	1.9371	22 Ω (INA225 gain = 25 V/V)
9.89E+05	–1.82%	1.4515	
2.25E+06	–1.73%	0.78564	
3.00E+06	–1.66%	0.61874	
5.99E+06	–1.78%	0.333	
8.97E+06	–1.44%	0.229	
1.53E+07	–2.43%	1.089	22 Ω (INA225 gain = 200 V/V)
2.24E+07	–2.55%	0.749	
2.99E+07	–2.68%	0.564	
3.96E+07	–3.17%	0.425	
4.96E+07	–3.26%	0.34	
5.93E+07	–3.51%	0.284	
6.92E+07	–3.74%	0.243	
7.90E+07	–3.75%	0.213	
8.87E+07	–4.21%	0.189	
9.84E+07	–4.47%	0.17	

8.3 Resistive Divider Approach

As Section 5.2 explains, the circuit has an option to measure the insulation resistance using the resistive divider approach. Figure 35 shows the accuracy results using the resistive divider approach,

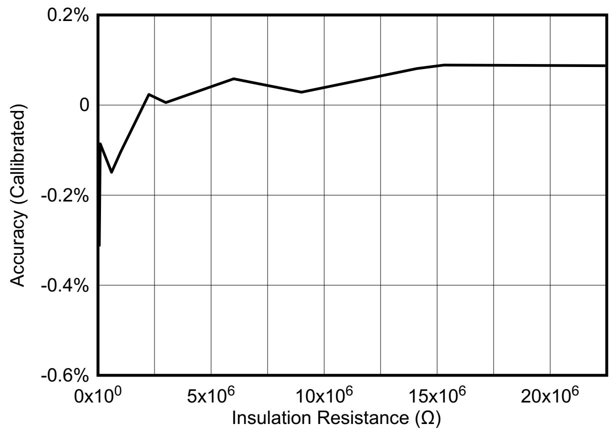


Figure 35. Accuracy for Resistive Divider Approach

As Table 7 shows, the % accuracy is < 1% for a range of 0 Ω to 22.49 MΩ, but the measured output is almost 3 mV to 4 mV different from the previous value. This difference in value means that a high-resolution ADC is required when using the resistive divider approach.

Table 7. Accuracy and Measurement Table for Resistive Divider Approach

INSULATION RESISTOR (IN MΩ)	MEASURED OUTPUT VOLTAGE (IN V)	% ACCURACY (CALIBRATED)
10000	0.0253	-0.56%
100000	0.20254	-0.09%
600000	0.65263	-0.15%
990000	0.79271	-0.11%
2250000	0.97345	0.02%
3000000	1.0186	0.01%
6000000	1.09569	0.06%
9000000	1.1235	0.03%
14100000	1.14537	0.08%
15300000	1.14847	0.09%
22490000	1.1599	0.09%

To summarize the accuracy graphs, the multiple-shunt approach provides good accuracy with the entire range covered for the insulation resistance.

8.4 Testing Fly-Buck Power Supply

Figure 36 shows the switch node waveform at V_{IN} = 15 V and Figure 37 shows the voltage output (3.3 V) from the non-isolated primary side of the Fly-Buck converter.

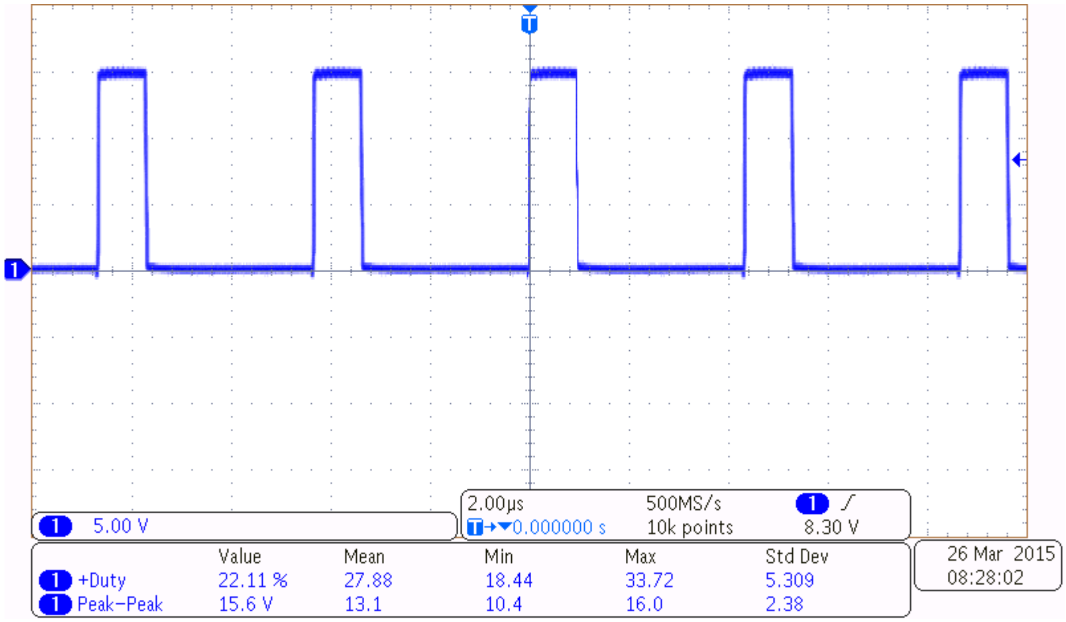


Figure 36. Switch Node Waveform at V_{IN} = 15 V

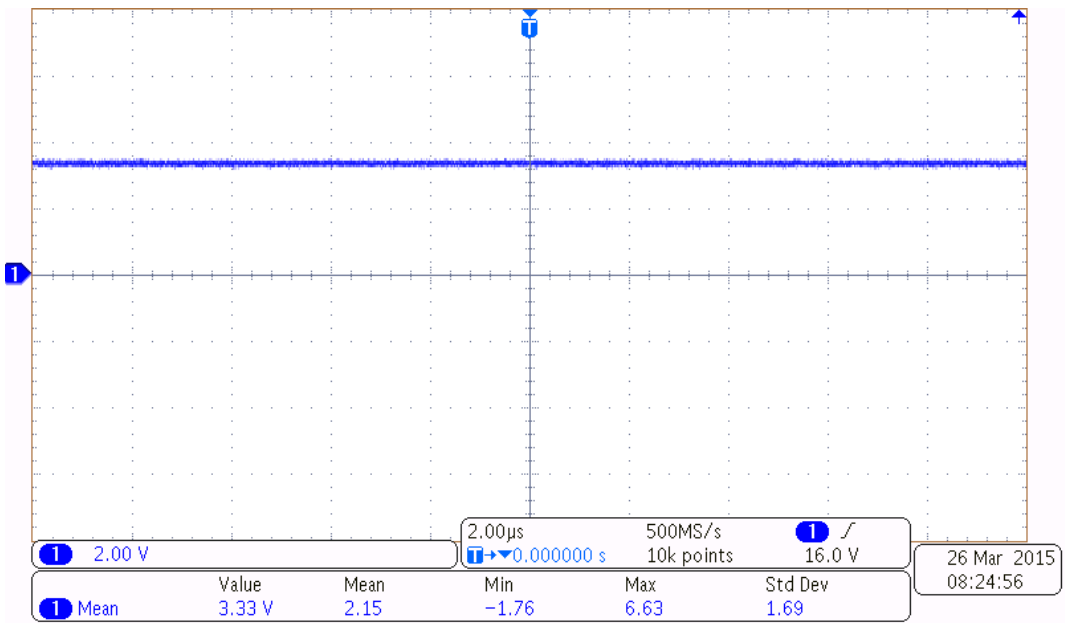


Figure 37. 3.3-V Waveform on Primary Side of LM5160 Fly-Buck Design

Figure 38 shows the voltage output (6V_VCC1) from the isolated secondary side of the Fly-Buck converter. Figure 39 shows the 5V_VCC1 derived from 6V_VCC1 using the TLV1117-50 device.

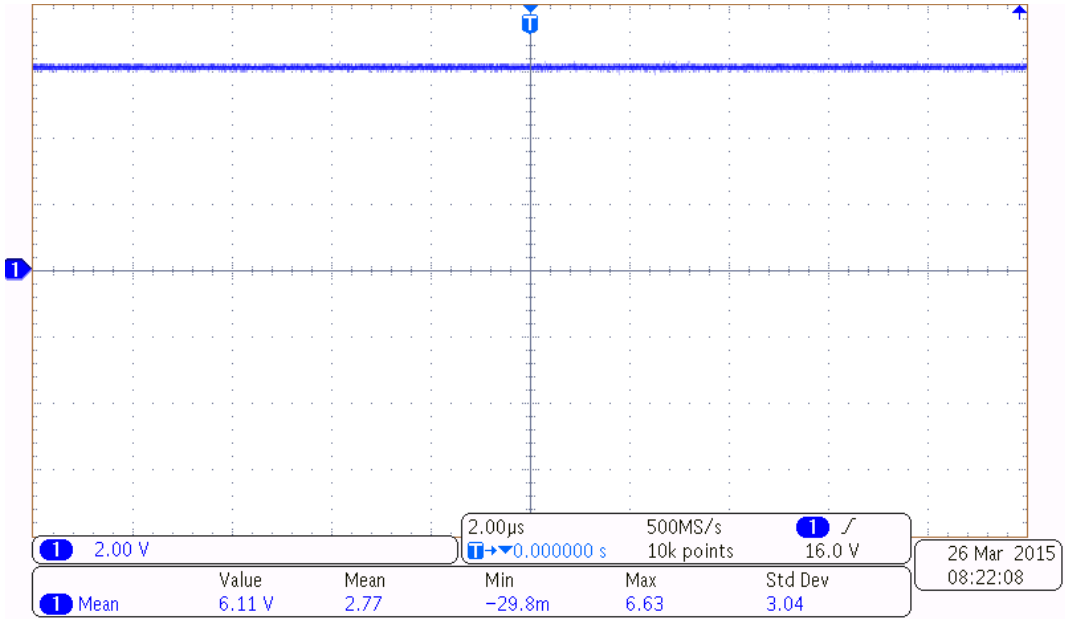


Figure 38. 6V_VCC1 Waveform

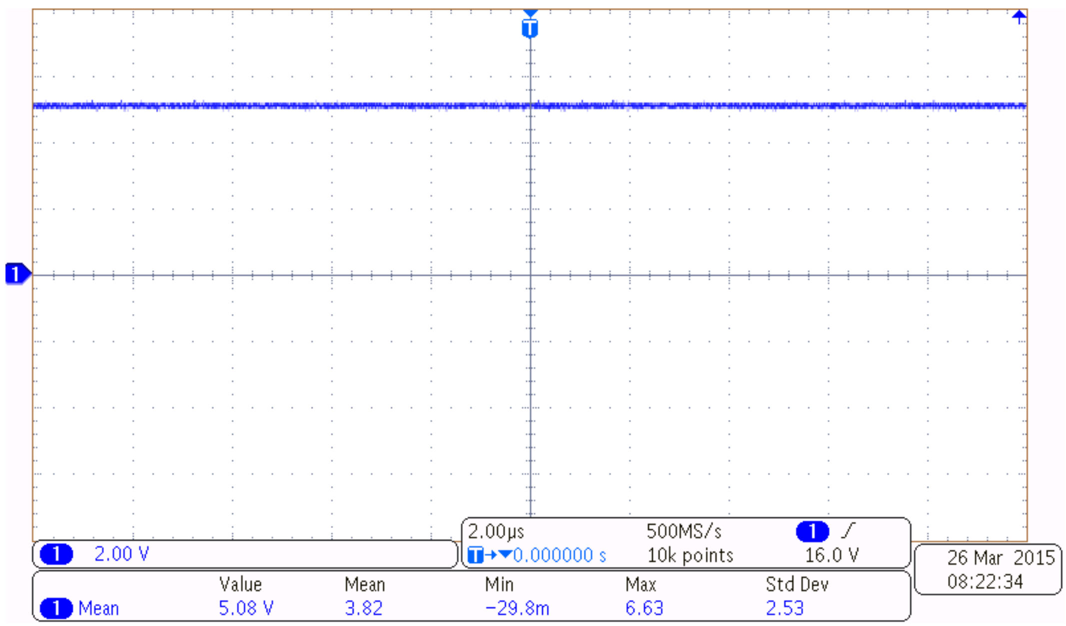


Figure 39. 5V_VCC1 Waveform

Figure 40 shows the voltage output (6V_VCC2) from the isolated secondary side of the Fly-Buck converter. Figure 41 shows the 5V_VCC2 derived from 6V_VCC2 using the LP2985A-5.0 device.

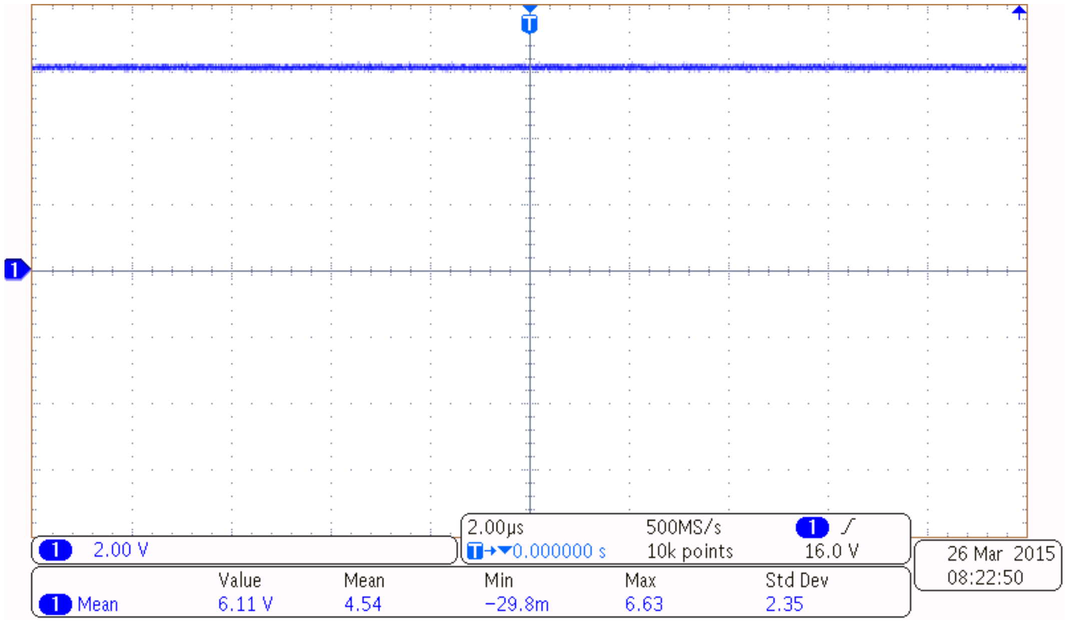


Figure 40. 6V_VCC2 Waveform

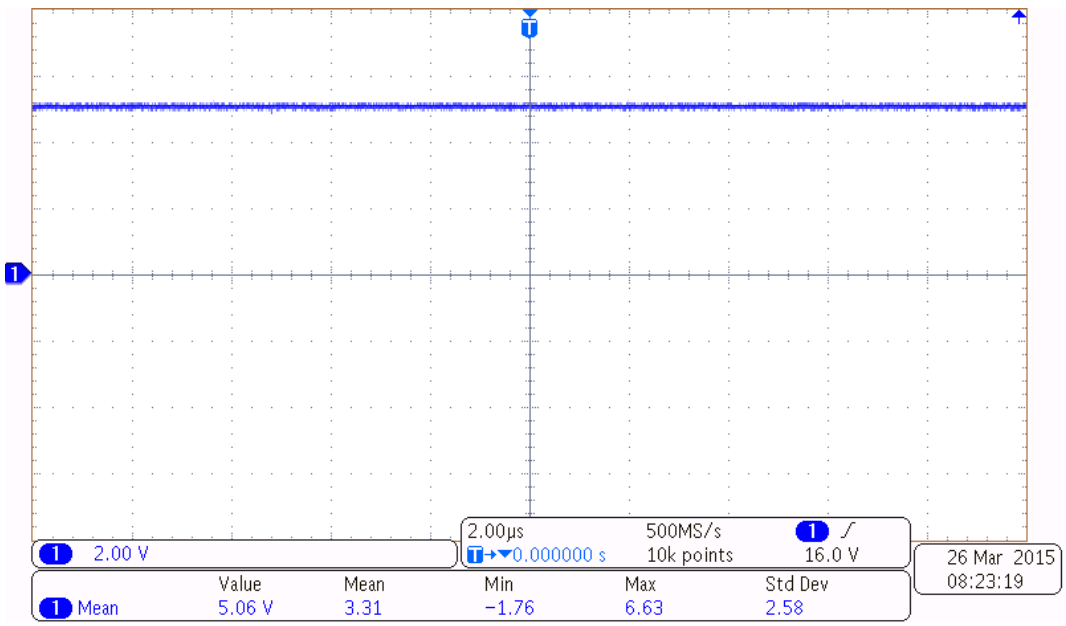


Figure 41. 5V_VCC2 Waveform

Now view the ripple voltage on each of the outputs. Figure 42 shows the ripple measured on a 3.3-V output on the primary side of the Fly-Buck converter.

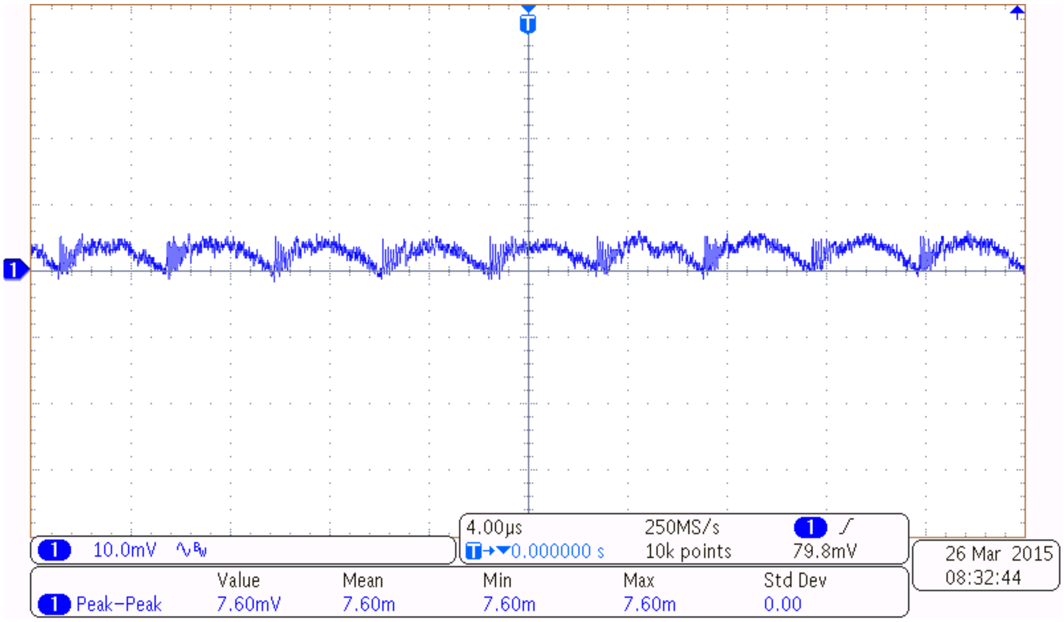


Figure 42. Ripple Measured on 3.3-V Output

Figure 43 and Figure 44 show the ripple on 6V_VCC1 and 5V_VCC1 respectively.

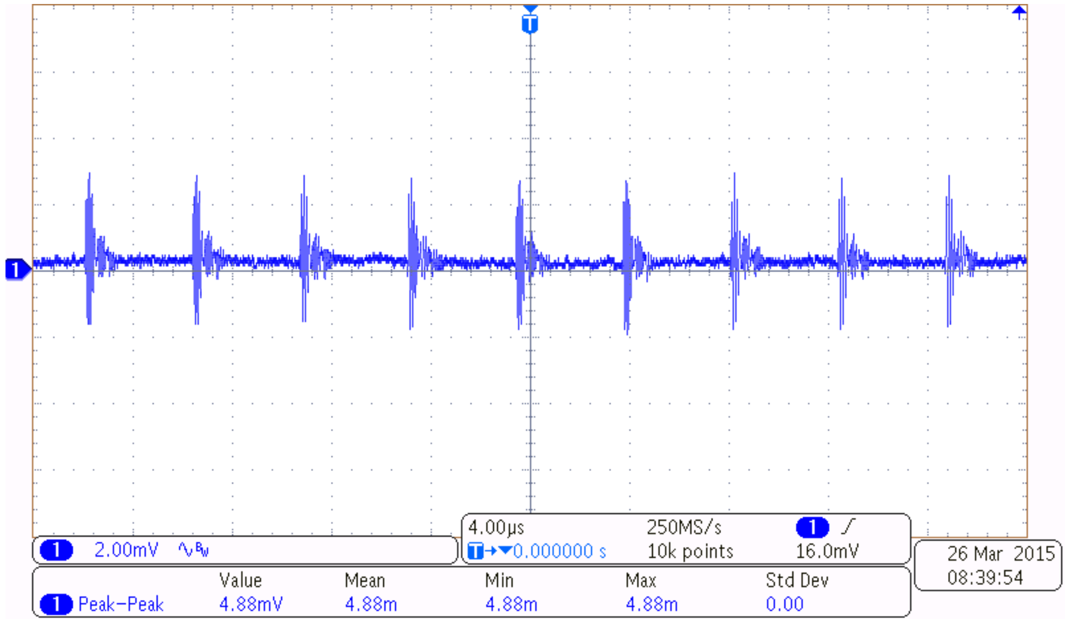


Figure 43. Ripple Measured on 6V_VCC1 Output

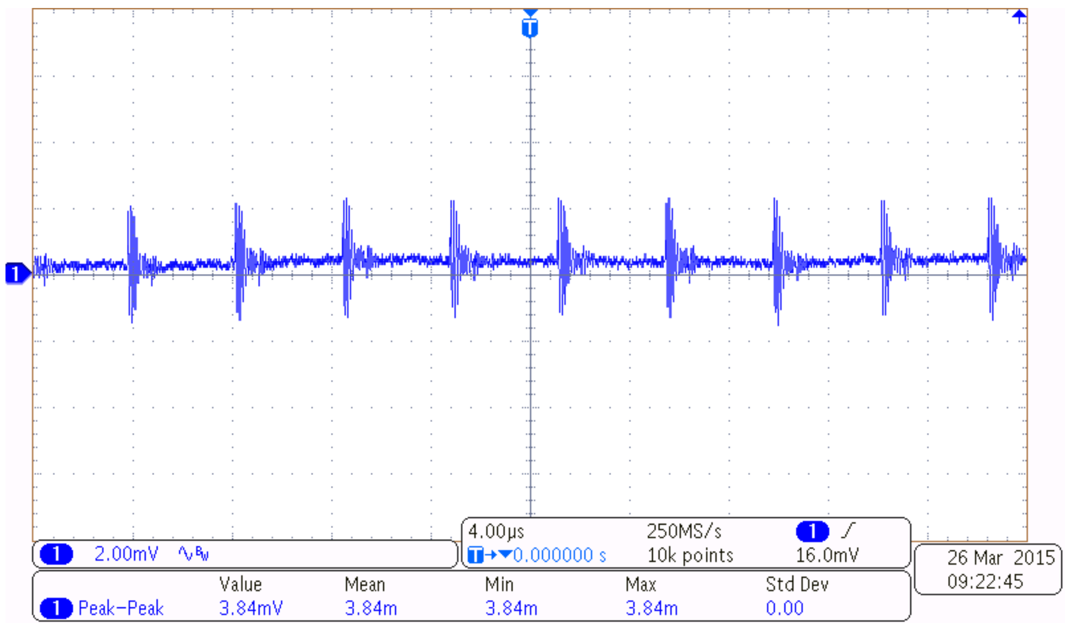


Figure 44. Ripple Measured on 5V_VCC1 Output

Figure 45 and Figure 46 show the ripple on 6V_VCC2 and 5V_VCC2 respectively.

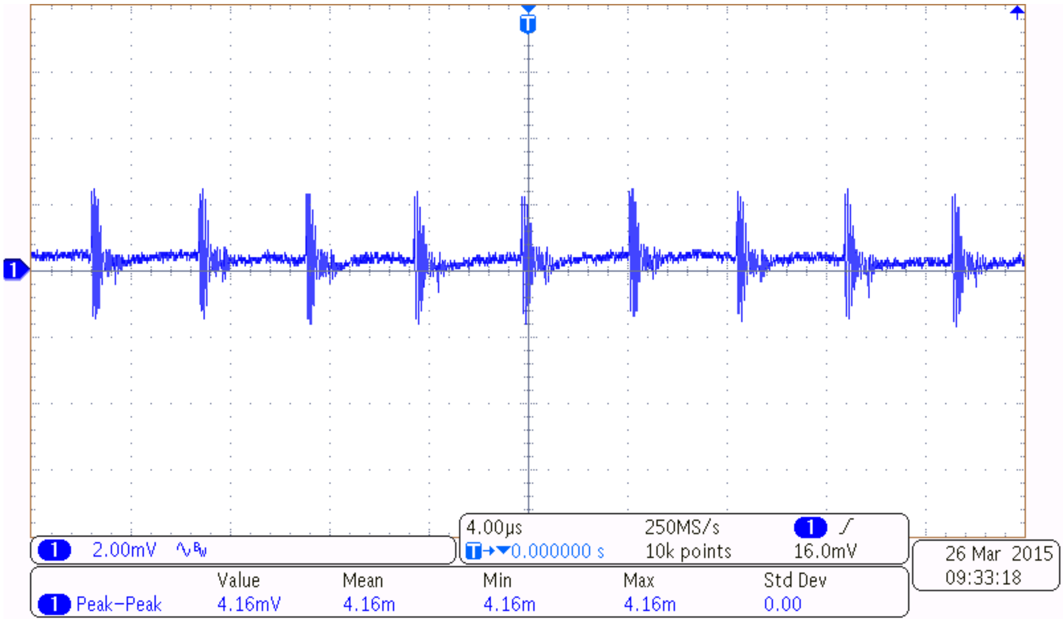


Figure 45. Ripple on 6V_VCC2 Output

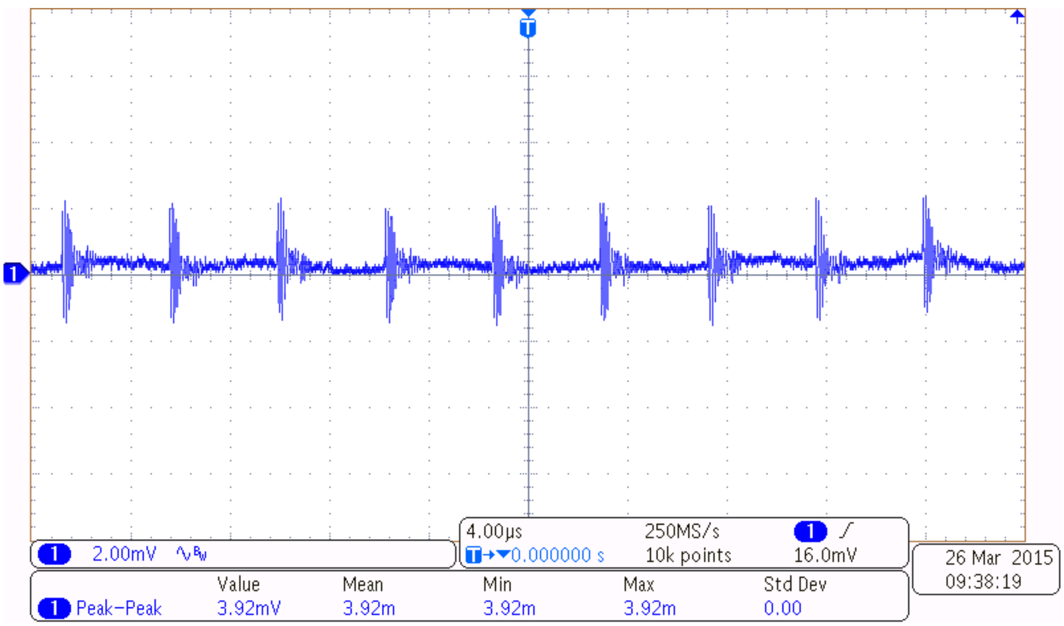


Figure 46. Ripple Measured on 5V_VCC2 Output

8.5 Testing TIDA-00440DB Flyback Power Supply

The flyback design was tested for line regulation at no-load condition and at a load of 1.5 mA. Figure 47 shows the regulation during no-load condition:

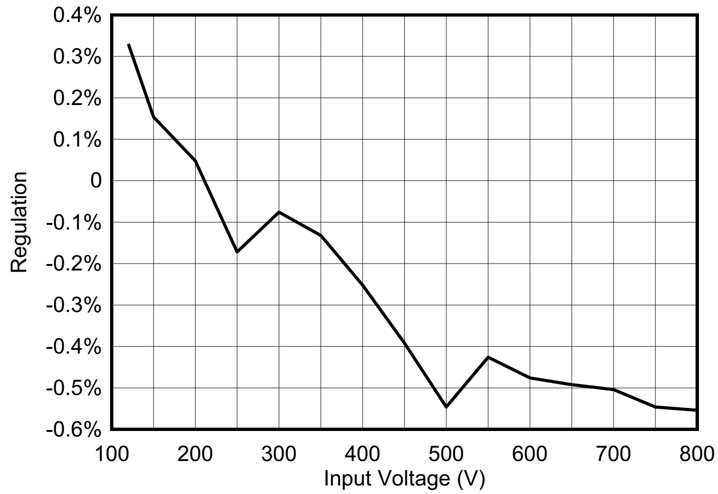


Figure 47. Line Regulation at No Load

Figure 48 shows the regulation with a load of 1.5 mA:

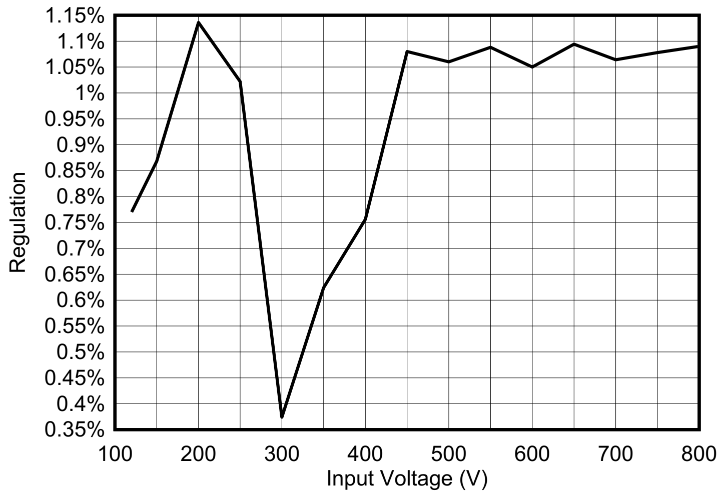


Figure 48. Line Regulation at Load = 1.5 mA

Figure 49 shows the output ripple at the no-load condition.

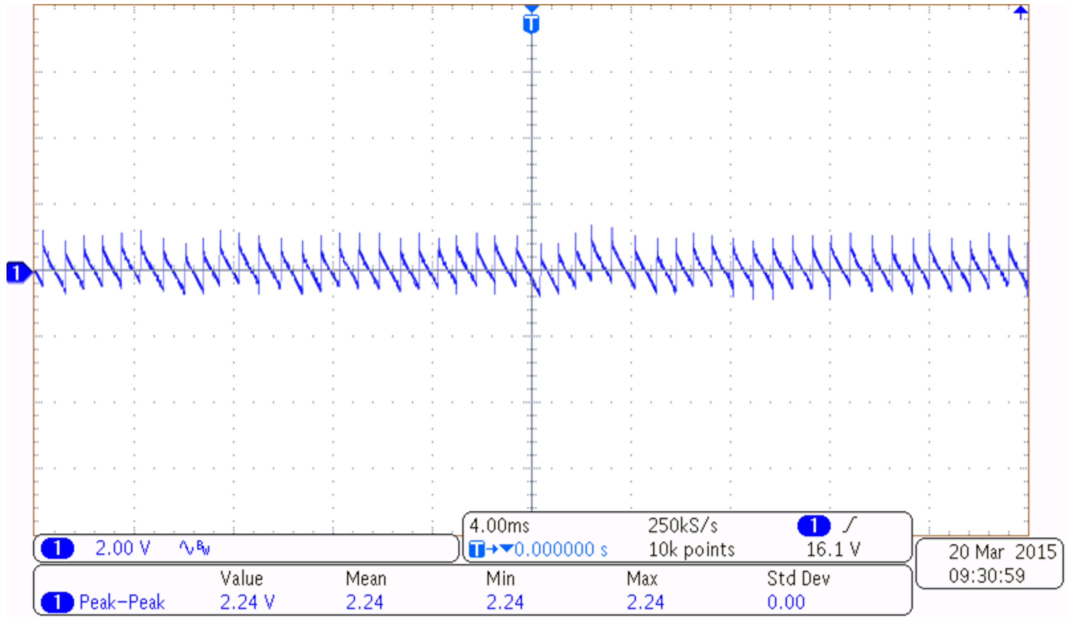


Figure 49. Output Ripple Waveform at No-Load

Figure 50 shows the output ripple at a load current of 1.5 mA.

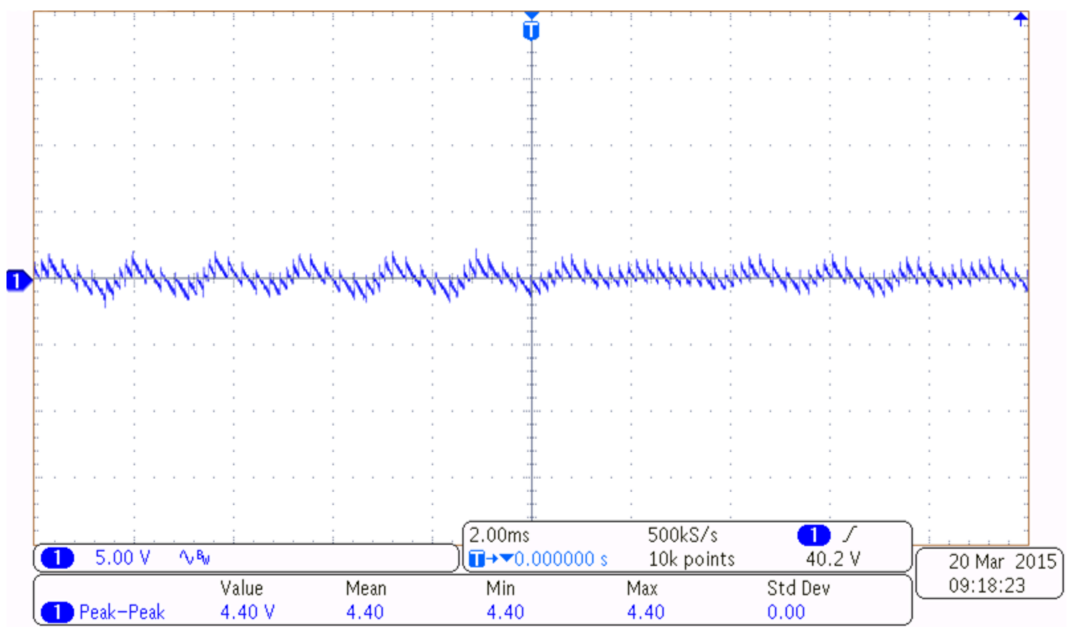


Figure 50. Output Ripple Waveform at Load = 1.5 mA

8.6 Testing With 2HP 3-Ph AC Induction Motor

As Figure 51 shows, the TIDA-00440 reference design was tested with a motor. The insulation resistance measurement takes place between one of the motor terminals (yellow wire in this example), and the frame of the motor (black wire). Figure 52 shows a zoomed-in version of the motor section. The motor used for this experiment is a 2-hp, three-phase AC induction motor. The insulation resistance of this motor (measured with high-resistance measurement equipment from Keithley) is 547 MΩ.

For the sake of measurement, one 100-MΩ resistance is connected in parallel with the motor insulation. The parallel combination is measured with the TIDA-00440 device. After doing this check, the insulation resistance is 547 MΩ || 100 MΩ = 84.54 MΩ (theoretically). Table 8 shows the actual values of insulation resistance measured with the single-shunt approach and the multiple-shunt approach.

Table 8. Insulation Resistance Measured With Motor

TEST CONDITION	VOLTAGE OUTPUT MEASURED	CORRESPONDING INSULATION RESISTANCE
Single-shunt approach (INA225 gain = 200, R_{SHUNT} = 22 Ω)	0.20953 V	83.497 MΩ
Multiple-shunt approach (R_{SHUNT} = 220 kΩ || 2.7 kΩ || 261 Ω), MUX = 1, removed 10-Ω resistors from the front filter of INA225)	1.154 V	85.65 MΩ

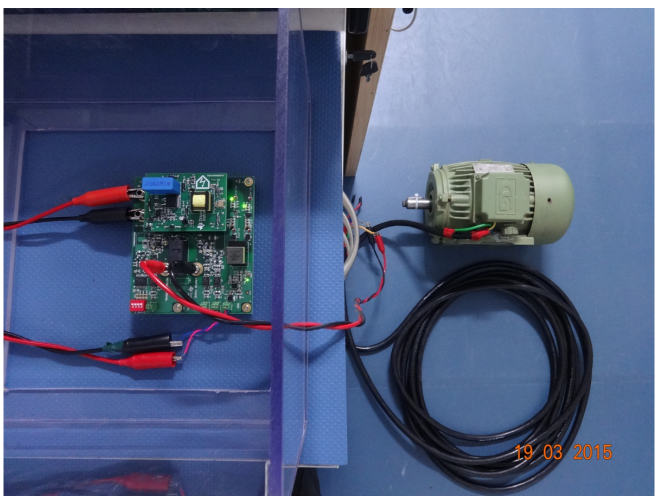


Figure 51. Motor Used for Testing TIDA-00440

Figure 52. Zoomed-In Photo of of Motor Used for Testing TIDA-00440

9 Design Files

9.1 Schematics

To download the schematics for each board, see the design files at http://www.ti.com/tool/TIDA-00440.

9.2 Bill of Materials

To download the bill of materials (BOM), see the design files at http://www.ti.com/tool/TIDA-00440.

9.3 PCB Layout Recommendations

An important thing to note is that the design contains high voltages up to 500 V and 800 V. The layout must be done with extreme care.

9.3.1 Layout Recommendations for TIDA-00440MB

The total size of the main board is 124.46 mm x 110 mm. Banana jacks J1 and J2 are used for an input voltage of 150-V DC to 800-V DC. J3 and J4 are used to connect the insulation resistance. Figure 53 shows how the clearances are provided on the PCB for the isolations.

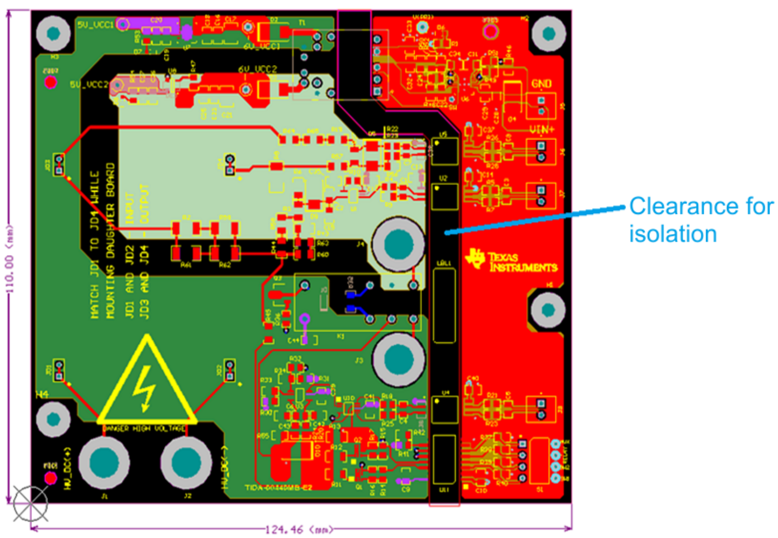


Figure 53. Clearance for Isolation

9.3.2 Layout Recommendations for LM5160 Fly-Buck Power Supply

A proper layout is essential for optimum performance of the circuit. Figure 54 shows the layout of the LM5160 Fly-Buck section.

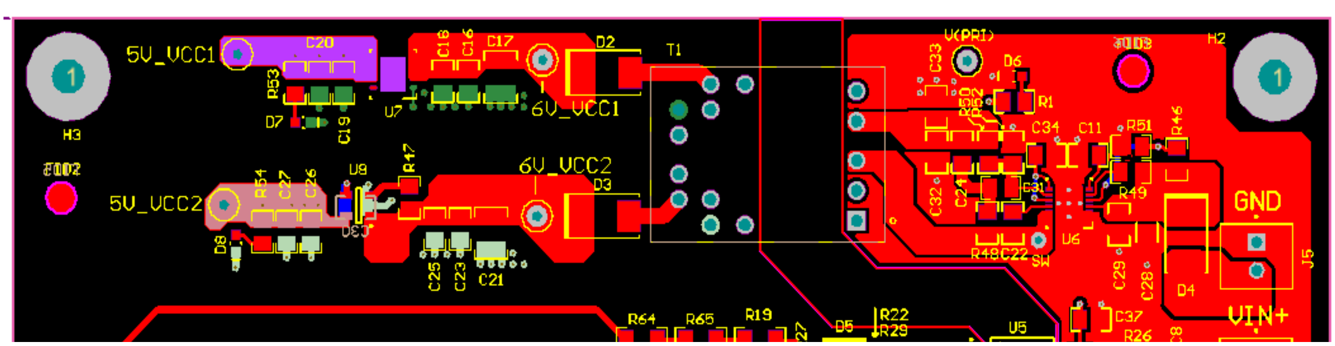


Figure 54. Layout for Fly-Buck Power Supply Section

In particular, the following guidelines must be observed:

- The loop consisting of the input capacitor, VIN pin, and PGND pin carries the switching current. Therefore, the input capacitor must be placed close to the IC, directly across the VIN and PGND pins. The connections to these two pins must be direct to minimize the loop area. In general, placing all of the input capacitances near the IC is not a possibilty. A good practice is to use a 0.1- to 0.47-µF capacitor directly across the VIN and PGND pins as close as possible to the IC with the remaining bulk capacitor.
- The VCC and bootstrap (BST) bypass capacitors supply switching currents to the high and low-side gate drivers. These two capacitors must also be placed as close to the IC as possible, and the connecting trace length and loop area must be minimized.
- The feedback trace carries the output voltage information and a small ripple component that is necessary for proper operation of the LM5160 device. Therefore, take care while routing the feedback trace to avoid coupling any noise into the feedback (FB) pin. In particular, the feedback trace must not run close to magnetic components, or parallel to any other switching trace.
- SW trace: The SW node switches rapidly between VIN and GND every cycle and is therefore a source of noise. The SW node area must be minimized. In particular, the SW node must not be inadvertently connected to a copper plane or pour.

Figure 55 shows a zoomed-in image of components near the LM5160 device.

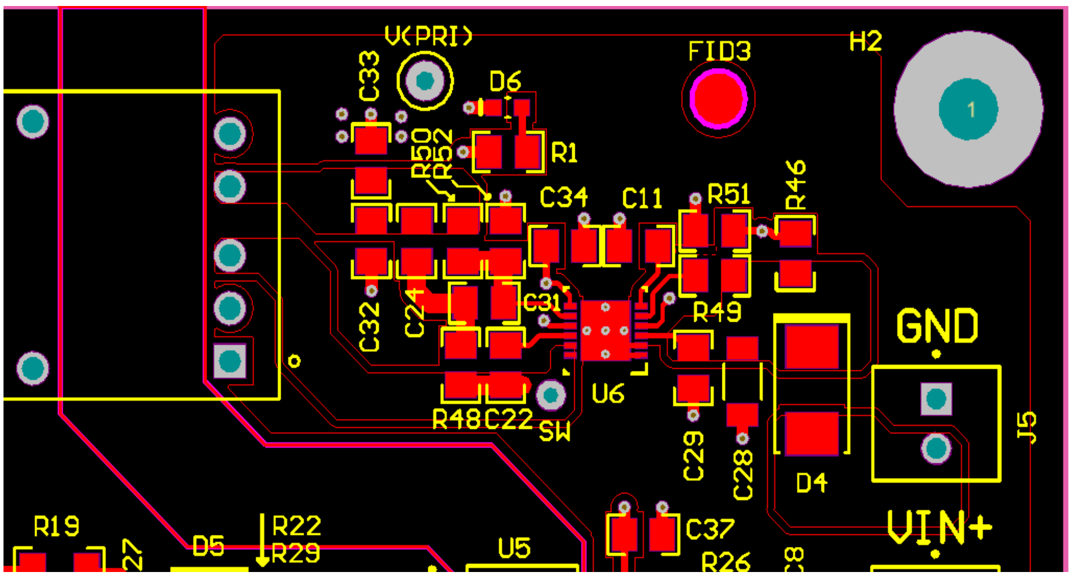


Figure 55. Component Placements Near LM5160

9.3.3 Layout Recommendations for TIDA-00440DB

A good layout is critical for proper functioning of the power supply. Figure 56 shows the overall layout of the daughter board. The total size of the daughter board is 75 mm x 52 mm.

Some critical points to note for the UCC28711 device are:

1. The loop of the current sense resistor, power MOSFET, transformer, and input bulk cap must be as small as possible (see Figure 57).
2. There must be a single point ground for the controller IC.
3. The control ground and power ground must be connected at a single point, which is the input bulk capacitor (see Figure 58 and Figure 59).

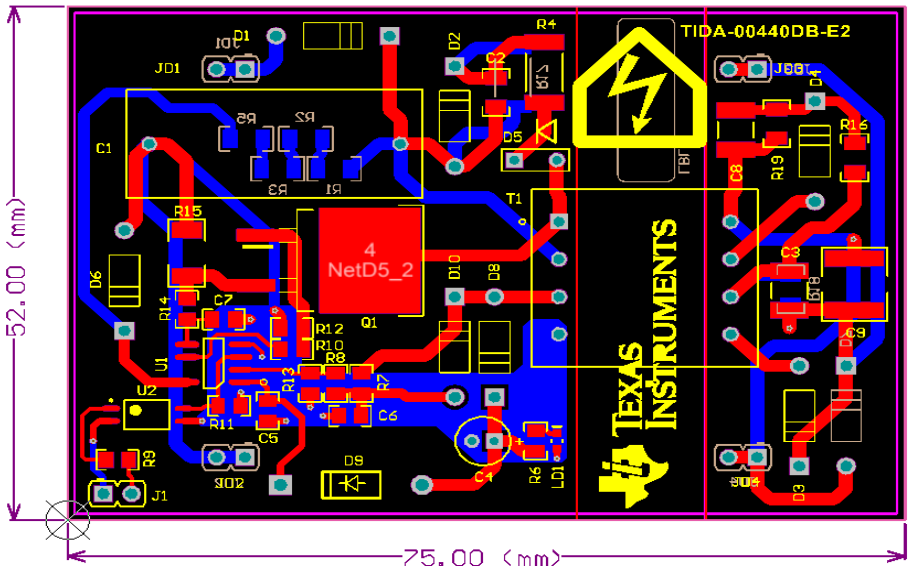


Figure 56. Layout for TIDA-00440DB

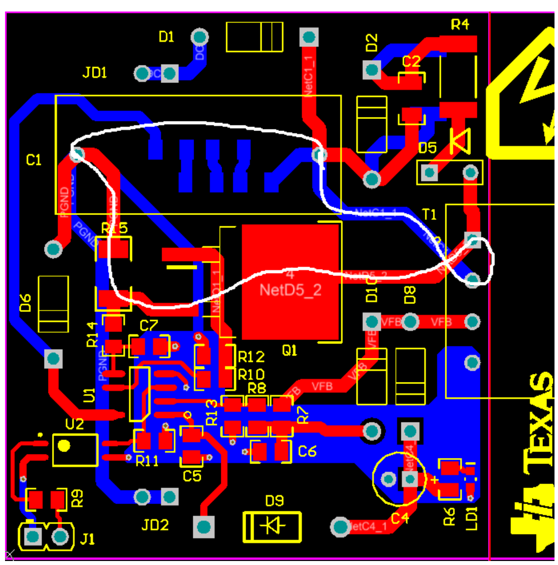


Figure 57. Power Loop Shown With White Line

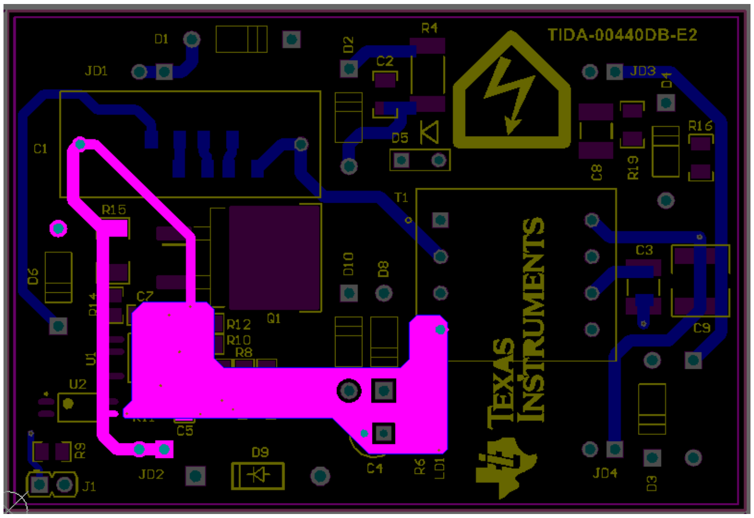


Figure 58. Single-Point Ground (Bottom Layer)

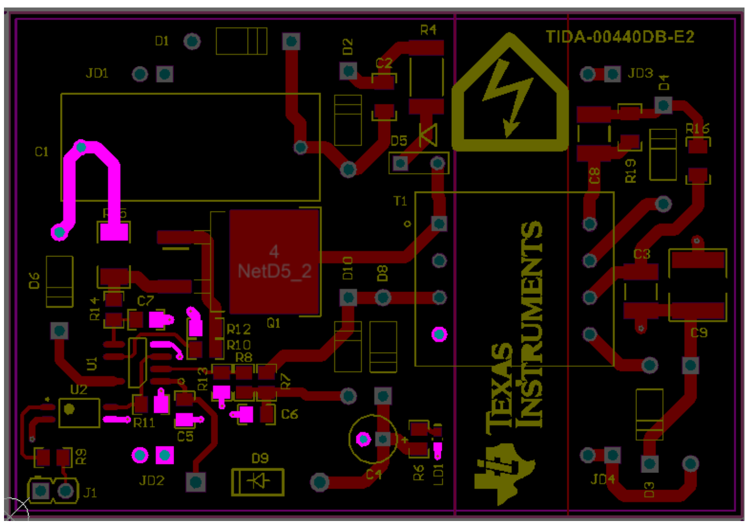


Figure 59. Single-Point Ground (Top Layer)

9.4 Layout Prints

To download the layout prints for each board, see the design files at http://www.ti.com/tool/TIDA-00440.

9.5 Altium Project

To download the Altium project files, see the design files at http://www.ti.com/tool/TIDA-00440.

9.6 Gerber Files

To download the Gerber files, see the design files at http://www.ti.com/tool/TIDA-00440.

9.7 Assembly Drawings

To download the assembly drawings, see the design files at http://www.ti.com/tool/TIDA-00440.

9.8 Software Files

To download the software files, see the design files at http://www.ti.com/tool/TIDA-00440.

10 References

1. IEEE.org, IEEE Standards Association, *43-2000 - IEEE Recommended Practice for Testing Insulation Resistance of Rotating Machinery*
2. Chafai, Mahfoud; Refoufi, Larbi; Bentarzi, Hamid; Signals and Systems Laboratory (SisyLab), *Medium Induction Motor Winding Insulation Protection System Reliability Evaluation and Im provement Using Predictive Analysis* , DGEE, FSI, University of Boumerdes, Algeria

11 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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Appendix A—Fly-Buck Power Supply

The Fly-Buck is basically a buck regulator with couple windings added to the inductor. The coupled windings can generate isolated outputs. The physical appearance of the Fly-Buck resembles a combination of a buck and flyback converter, hence the name Fly-Buck (Figure 60). The operation on the primary side is similar to the buck, while the secondary side output is clamped by the primary output. The Fly-Buck operation in a switching cycle can be divided into on-time and off-time, as Figure 61 shows.

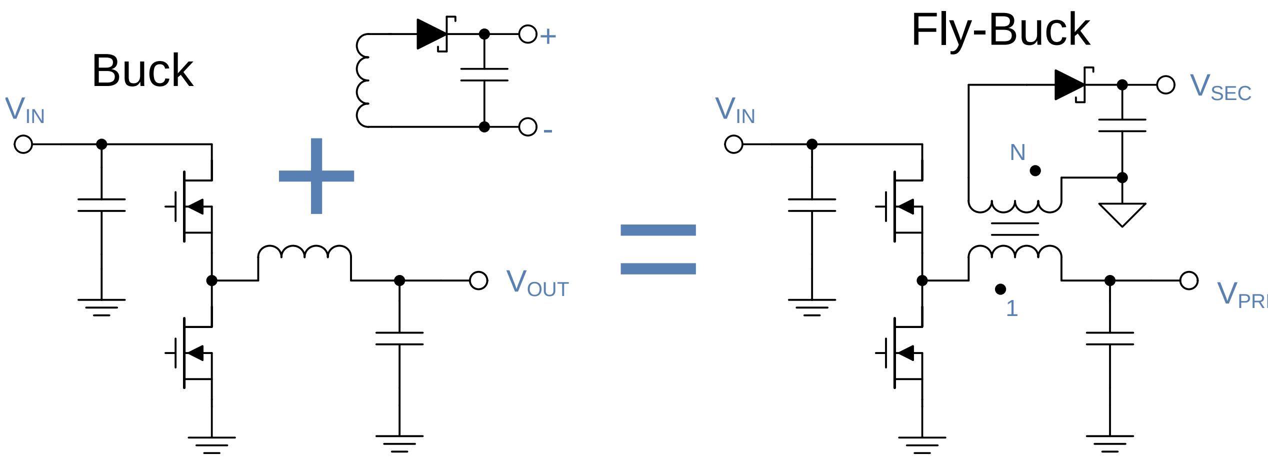

Figure 60. From Buck to Fly-Buck

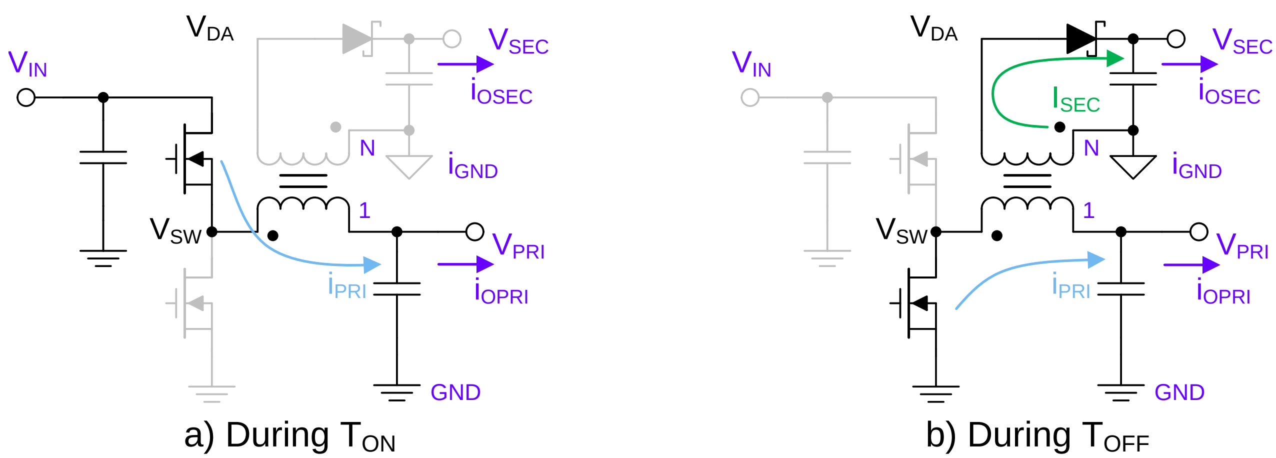

Figure 61. The Fly-Buck in ON and OFF time

During T_{ON}, the rectifier diode is in reverse bias, so the secondary side is cut off from the primary. The primary side operates similarly as it does in a buck regulator; the transformer primary current rises linearly. The primary output voltage is $V_{pri} = D \times V_{IN}$. During T_{OFF}, the diode is forward biased and conducts. The current can flow in the primary and secondary side simultaneously; however, the magnetizing current in the transformer is still in the triangle waveform, which can be calculated as the combination of the primary and secondary winding current as defined by Equation 2:

$$i_m = i_{PRI} + Ni_{SEC} \tag{2}$$

The primary side output clamps the secondary output voltage, $V_{SEC} = N \times V_{PRI}$. View the steady-state operation waveforms of a Fly-Buck in Figure 62.

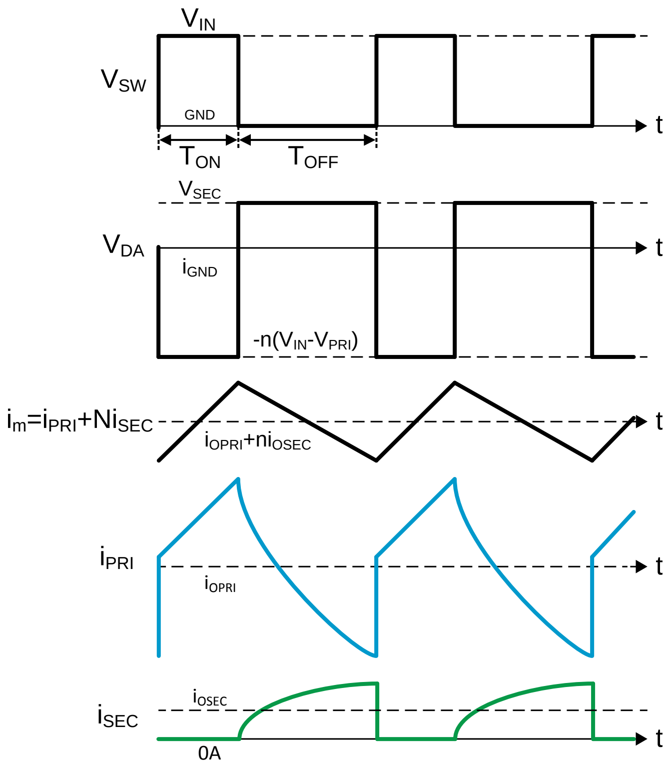

Figure 62. Fly-Buck Operation Waveform

From the preceding analysis, the magnetizing current ripple can be derived as Equation 3:

$$\Delta i_m = \frac{V_{PRI}}{L_{PRI}} \frac{1 - D}{f_{SW}} \tag{3}$$

where

- L_{PRI} = Primary inductance
- $D = T_{ON} / (T_{ON} + T_{OFF})$ = Duty cycle
- f_{SW} = Switching frequency

Equation 4 calculates the peak current of the primary side as:

$$i_{m\_PEAK} = i_m + \frac{1}{2}\Delta i_m = i_{opri} + (N \times i_{osec}) + \frac{1}{2}\Delta i_m \tag{4}$$

where

- i_{opri} = Average primary output current
- i_{osec} = Average secondary output current

If multiple outputs are involved, each secondary output must be converted to the primary side by multiplying the corresponding turns-ratio — Equation 2 is still applicable.

Appendix B—PSR Flyback Power Supply

The UCC28711 is a PSR flyback controller. In primary-side control, the output voltage is sensed on the auxiliary winding during the transfer of transformer energy to the secondary. To achieve an accurate representation of the secondary output voltage on the auxiliary winding, the discriminator (inside UCC28711) reliably blocks the leakage inductance reset and ringing, continuously samples the auxiliary voltage during the down slope after the ringing is diminished, and captures the error signal at the time the secondary winding reaches zero current. The internal reference on VS is 4.05 V; and VS is connected to a resistor divider from the auxiliary winding to the ground. The output-voltage feedback information is sampled at the end of the transformer secondary-current demagnetization time to provide an accurate representation of the output voltage. Timing information to achieve valley switching and to control the duty cycle of the secondary transformer current is determined by the waveform on the VS pin. TI does not recommend to place a filter capacitor on this input, which would interfere with accurate sensing of this waveform. The VS pin senses the bulk-capacitor voltage to provide for AC-input run and stop thresholds. The VS pin also compensates the current-sense threshold across the AC-input range. The VS pin information is sensed during the MOSFET on-time. For the AC-input run or stop function, the run threshold on VS is 225 µA and the stop threshold is 80 µA. A wide separation of run and stop thresholds allows clean startup and shutdown of the power supply with the line voltage. The values for the auxiliary voltage divider upper-resistor R_{S1} and lower-resistor R_{S2} can be determined by Equation 5 and Equation 6.

$$R_{S1} = \frac{V_{IN\_RUN}}{N_{PA} \times I_{VSL\_RUN}}$$

where

- N_{PA} is the transformer primary-to-auxiliary turns ratio
- V_{IN_RUN} is the converter input start-up (run) voltage
- I_{VSL_RUN} is the run threshold for the current pulled out of the VS pin during the MOSFET on-time (equal to 220 µA max from the UCC28711 data sheet) (5)

$$R_{S2} = \frac{R_{S1} \times V_{VSR}}{N_{AS} \times (V_{OCV} + V_F) - V_{VSR}}$$

where

- V_{OCV} is the regulated output voltage of the converter
- V_F is the secondary rectifier forward voltage drop at near-zero current
- N_{AS} is the transformer auxiliary-to-secondary turns ratio
- R_{S1} is the VS divider high-side resistance
- V_{VSR} is the CV regulating level at the VS input (equal to 4.05 V typical from the UCC28711 data sheet) (6)

The UCC28711 device operates with cycle-by-cycle primary-peak current control. The normal operating range of the CS pin is 0.78 V to 0.195 V. There is additional protection if the CS pin reaches 1.5 V, which results in a UVLO reset and restart sequence. The current-sense (CS) pin is connected through a series resistor (R_{LC}) to the current-sense resistor (R_{CS}). The current-sense threshold is 0.75 V for I_{PP_MAX} and 0.25 V for I_{PP_MIN}. The series resistor R_{LC} provides the function of feed-forward line compensation to eliminate any change in IPP due to change in di/dt and the propagation delay of the internal comparator and MOSFET turnoff time. There is an internal leading-edge blanking time of 235 ns to eliminate sensitivity to the MOSFET turn-on current spike. The value of R_{CS} is determined by the target output current in constant-current (CC) regulation, as Equation 7 shows. The value of R_{LC} is determined by Equation 8.

$$R_{CS} = \frac{V_{CCR} \times N_{PS}}{2I_{OCC}} \times \sqrt{\eta_{XFMR}}$$

where

- R_{CS} is the current sense resistor value
- V_{CCR} is the current regulation constant (equal to 330 mV typical from the UCC28711 data sheet)
- N_{PS} is the transformer primary-to-secondary turns ratio
- I_{OCC} is the target output current in constant-current regulation
- η_{XFMR} is the transformer efficiency (7)

$$R_{LC} = \frac{K_{LC} \times R_{S1} \times R_{CS} \times T_D \times N_{PA}}{L_P}$$

where

- R_{LC} is the line compensation resistor
- R_{S1} is the VS pin high-side resistor value
- R_{CS} is the current-sense resistor value
- T_D is the current-sense delay including MOSFET turn-off delay (add 50 ns to the MOSFET delay)
- N_{PA} is the transformer primary-to-auxiliary turns ratio
- L_P is the transformer primary inductance
- K_{LC} is the current-scaling constant (equal to 25 A/A according to the data sheet of UCC28711) (8)