TI Designs
30-W Ultra-Wide Range Power Supply for Protection Relay

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TPS40210	Product Folder
UCC28600	Product Folder
LMS33460	Product Folder
LM337	Product Folder
TL431A	Product Folder

Featured Applications

- Power Supply for Numerical Protection
- Power Supply for Substation IED and Automation Products

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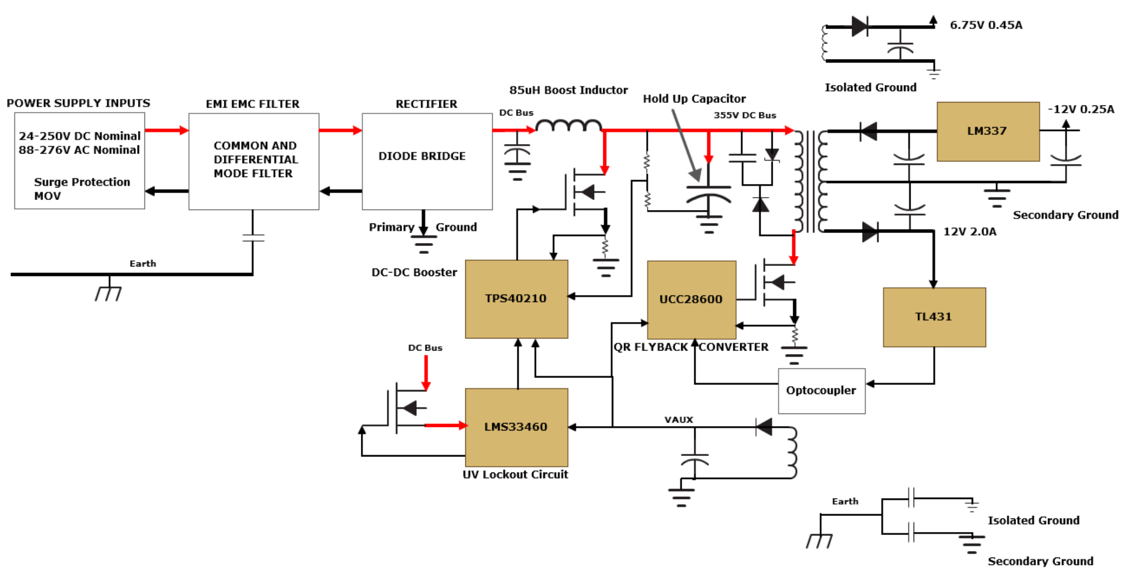
Design Features

The 30-W Ultra-Wide Range Power Supply is a reference design for numerical protection relay. This design is a single board power solution that handles an ultra-wide range of both AC and DC inputs.

- Nominal Input Supply Voltage (Un)
  – 24 to 250-V DC and 88 to 276-V AC
- Output Rails at Nominal Supply Voltage
  – 12 V at 2 A and –12 V at 0.25 A
  – Isolated 6.75 V at 0.45 A
  – Total Output Power 30 W
  – Line Regulation < ±3%
    - 20 to 250-V DC and 80 to 276-V AC
  – Load Regulation (10 to 100%) < ±3%
  – PCB Dimension 200 × 100 mm
- Meets Pre-compliance Test Requirements:
  – IEC61000-4 for EFT and Surge
  – CISPR 11 /EN 55011 Class A for Conducted Emission
  – IEC61000-4-11 (AC) and IEC61000-4-29 (DC) for Voltage Dips and Interruptions with Reduced Bulk Capacitor Value



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1 System Description

Protection relays play a critical role in electrical grid, substation, and distribution power systems. These relays protect the electrical power system against different electrical faults. The heart of this protection is a smart controlling unit that continuously monitors electrical parameters such as voltages, currents, and frequencies. The smart controlling unit also issues trip commands to appropriate circuit breakers during faults. There are different types of relays, depending upon the stage used, such as generator protection, distance protection, overvoltage protection, overcurrent protection, and differential protection.

Protection relays are either self-powered or auxiliary powered.

This design guide provides details to design an auxiliary power supply for protection relay.

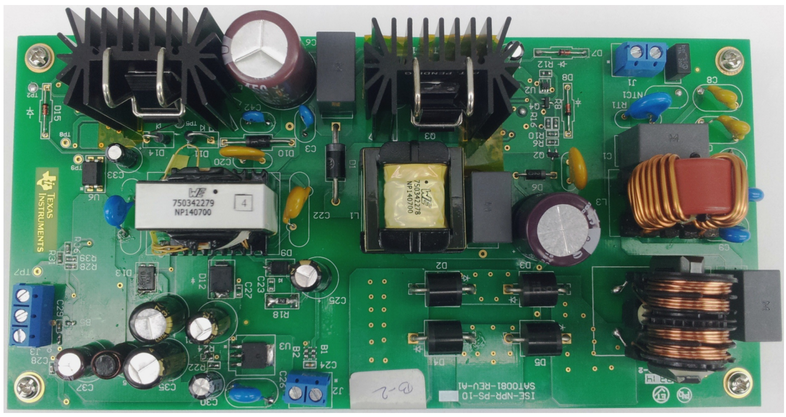


Figure 1. 30-W Ultra-Wide Range Power Supply for Protection Relay

1.1 Power Supply Input Voltage Types

The auxiliary input voltage for protection relays are generally categorized by the following types:

Type 1

If the substation is equipped with a battery supply, then the nominal power supply to the protection relay is:

- Low Voltage DC: 24-V DC or 48-V DC or 60-V DC
- High Voltage DC: 110-V DC or 220-V DC or 250-V DC

Type 2

For the substation not supplied with a battery, the AC power supply is used for auxiliary supply. The AC supply depends on the area and the location of the relay. General typical voltages are 110 V, 220 V, 230 V, and 240 V.

The output load for the protection relay can vary from ≤ 10 W to around 30 W based upon type of relay. A protection relay with only overcurrent protection can have ≤ 10-W load. A protection relay with multiple protection functions and communication options can have around 30-W load.

1.2 Critical Requirement

A protection relay must meet voltage dips and interruption test requirements at nominal input voltage according to IEC61000-4-11 (AC) and IEC61000-4-29 (DC). These requirements are critical for relays with higher power consumption. As the load increases, the size of bulk capacitor at the DC bus increases. The increase in the bulk capacitor size causes the following problems:

- A high value for the bulk capacitor size increases the inrush current significantly, which can reduce the reliability of the power supply if care is not taken.

The proposed design reduces the size of the bulk capacitor, in compliance with IEC61000-4-11 (AC) and IEC61000-4-29 (DC), for voltage variation and interruption testing.

2 Design Requirements

Typical power supply specifications follow.

Functional requirement	Output power	30 W
	Input voltage DC	24 to 250-V DC
	Input voltage AC	88 to 276-V AC
	Output voltages and load	12 V at 2 A –12 V at 0.25 A Isolated 6.75 V at 0.45 A
	Load regulation	< ±3%
	Line regulation	< ±3%
	Output ripple	< 200 mV pk-pk for ±12 V
Precompliance	Conducted emission	CISPR 11 / EN55011 Class A
	EFT	IEC 61000-4-4
	Surge	IEC 61000-4-5
Performance Requirement	Maximum interruption time in the auxiliary DC voltage for 50 ms	> 75 ms after auxiliary input voltage falls to zero

3 Block Diagram

The 30-W power-supply design can handle an ultra-wide range of both AC and DC inputs, making the power supply design a suitable platform for a variety of protection relays. The power supply is designed to output industry standard voltages required in protection relays. The power supply also provides excellent line and load regulation. This solution has been designed for 30-W power supply with good efficiency. The design has been pre-compliance tested for IEC61000-4 (EFT and Surge) and CISPR 11 / EN55011 Class A (Interference).

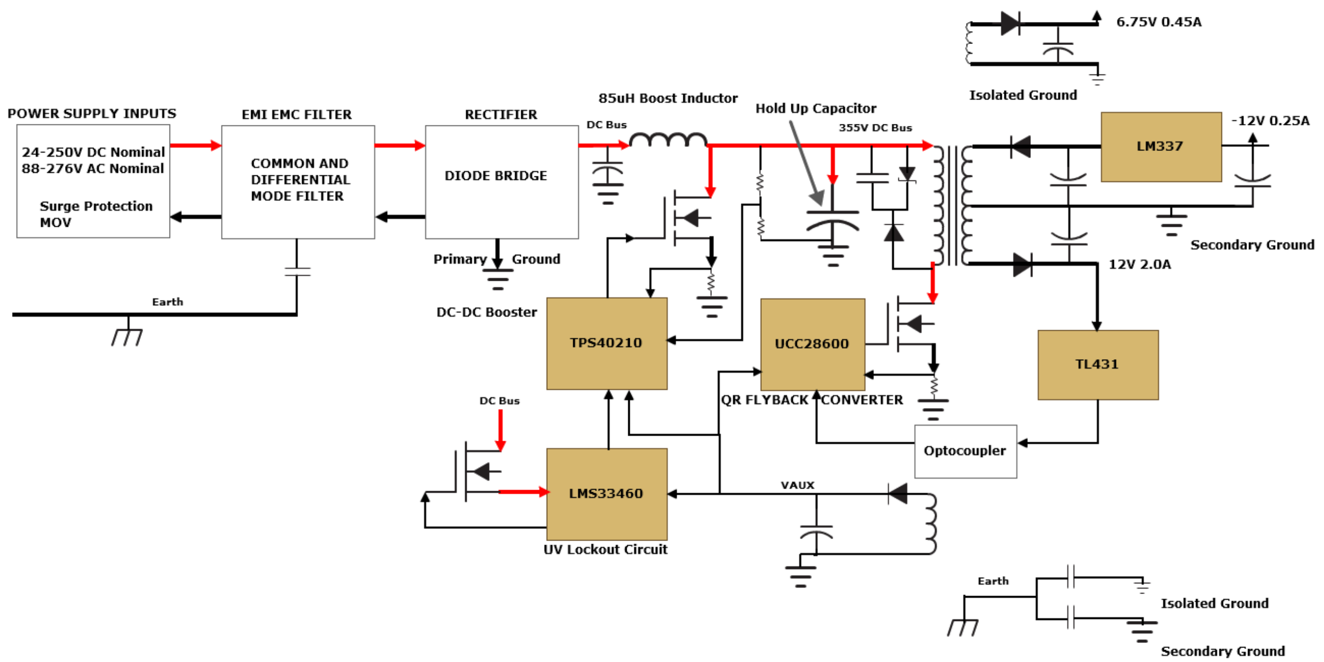


Figure 2. Block-Level Design

The design uses a two-stage conversion topology. The design includes a DC-DC boost converter which boosts input voltage (24 to 250-V DC input or rectifier 88 to 276-V AC input) to the 355-V DC output. The DC voltage is the input to a quasi-resonant flyback converter. The outputs of the flyback converter are ±12 V and isolated 6.75 V.

The power supply design has following the blocks.

Power Supply Inputs and Filter

The board has a single input connector for DC and AC voltages. The board has a front-end EMC filter. The board has surge protection circuits with a metal-oxide varistor (MOV) for differential mode surge, common mode surge, and common mode choke. The board has Y capacitors for common mode filtering. The board uses an X capacitor and leakage inductance of common mode choke for differential mode filtering.

Input Rectifier

Because of an ultra-wide range of DC inputs, the current drawn by the power supply at the lower input rail is approximately 20 V is 2 to 3 A. To achieve efficiency, the design uses a discrete diode bridge for optimum power dissipation and less efficiency loss across the bridge rectifier.

Booster

The DC output of the bridge rectifier is applied to a DC-DC booster using a TPS40210 current-mode controller. The TPS40210 controller works in discontinuous conduction mode. The output of the booster is 355-V DC for 24 to 250-V DC input or 88 to 276-V AC input. The discontinuous mode is chosen to avoid losses because of continuous conduction mode (CCM) mode.

Flyback Converter

The second stage is a flyback converter using TI UCC28600 green-mode controller. The second stage has 355-V DC input. The outputs of the flyback converter are as follows.

- 12 V, 2 A
- –12 V, 0.25 A
- Isolated 6.75 V, 0.45 A
- Total output power 30 W

The flyback converter has an operating input range of 100 to 355-V DC, at all input voltage levels. The converter reduces the bulk capacitor size required to meet the voltage interruption test to comply with IEC 61000-4-11.

The design uses Snubber circuits to minimize the transients across the DC-DC booster MOSFET, flyback converter MOSFET, and output diodes. These circuits also reduce EMI.

4 Circuit Design and Component Selection

4.1 Front-End EMC Filter

For calculation of the EMC filter and other EMC consideration, see the following application notes available at the TI website:

- *Designing Magnetic Components for Optimum Performance in Low-Cost AC/DC Converter Applications*, SLUP265
- *AN-2162 Simple Success With Conducted EMI From DC-DC Converters*, SNVA489C
- *Understanding and Optimizing Electromagnetic Compatibility in Switchmode Power Supplies*, SLUP202

4.2 DC-DC Booster Design

The DC-DC booster is configured using the TPS40210 controller. The TPS40210 device is a wide-input voltage (4.5 to 52-V), nonsynchronous boost controller.

The TPS40210 device is suitable for topologies that require a grounded source N-channel FET including boost, flyback, SEPIC, and various LED driver applications. Current mode control provides improved transient response and simplified loop compensation.

The following are features of the DC-DC booster.

- Adjustable oscillator frequency
- Fixed frequency current mode control
- Internal slope compensation
- Integrated low-side driver
- Programmable closed loop soft start
- Overcurrent protection
- External synchronization capability
- Reference 700 mV (TPS40210)
- Low current disable function

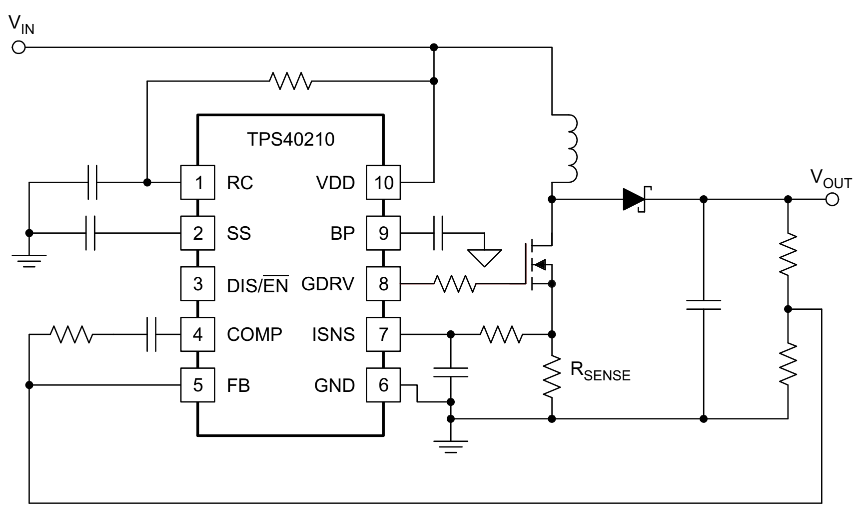


Figure 3. DC-DC Booster Design Using theTPS40210DGQ

4.2.1 Power Supply Design Parameters

1. Input voltage DC: 24 to 250-V DC nominal
2. Input voltage AC: 88 to 276-V AC nominal
3. Output rails
   - 12 V, 2 A
   - –12 V, 0.25 A
   - Isolated 6.75 V, 0.45 A

4.2.2 DC-DC Booster Design Calculation

The calculations listed in this section are for the booster inductor, based on the TI application note, SLUP127.

1. Booster Design Parameters

- Minimum DC input voltage, (V):

$$V_{INDCMIN} = 18\ V \tag{1}$$

- Maximum DC input voltage, (V):

$$V_{INDCMAX} = 250\ V \tag{2}$$

- Minimum AC input voltage, (V):

$$V_{INACMIN} = 80\ V \tag{3}$$

- Maximum AC input voltage, (V:

$$V_{INACMAX} = 276\ V \tag{4}$$

- Bridge rectifier drop, (V):

$$V_{BR} = 0.7\ V \tag{5}$$

- Bus voltage, (V):

$$V_{BUS} = V_{INAC} \times 1.4142 - 2 \times V_{BR} \tag{6}$$

$$V_{BUS} = V_{INDC} - 2 \times V_{BR} \tag{7}$$

$$V_{BUS} = 16.6\ V - 389\ V\ DC \tag{8}$$

- Second stage output power:

$$P_{FLYBACKOUT} = 30\ W \tag{9}$$

- Efficiency of booster:

$$\tau 2 = 0.8 \tag{10}$$

- Input power of booster:

$$P_{BOOSTERIN} = 47\ W \tag{11}$$

- Output voltage of the booster:

$$V_{BOOSTOUT} = 355\ V \tag{12}$$

- Average current of the booster:

$$I_{BOOSTOUT} = \frac{P_{BOOSTEROUT}}{V_{BOOSTOUT}} = \frac{38}{355} = 0.106\ A \tag{13}$$

- Output load of the Booster:

$$R_{BOOSTOUT} = \frac{V_{BOOSTOUT}}{I_{BOOSTOUT}} = 3361\ \Omega \tag{14}$$

2. Preliminary Calculation

- Voltage gain of the booster:

$$M_{MAX} = \frac{V_{BOOSTOUT}}{V_{BUSMIN}} = \frac{355}{16.6} = 21.39 \tag{15}$$

$$M_{MIN} = \frac{V_{BOOSTOUT}}{V_{BUSMAX}} = \frac{355}{389} = 0.91 \tag{16}$$

- Duty cycle:

$$D_{MAX} = 1 - \frac{1}{M_{MAX}} = 0.95 \tag{17}$$

- Switching frequency, (Hz):

$$F_{SW} = 35000 \tag{18}$$

- Time periods:

$$T_{SW} = 28.57\ \mu s \tag{19}$$

- Critical inductor value to keep in discontinuous mode:

$$L_{CRITICAL} \leq 0.5 \times R_{BOOSTOUT} \times T_{SW} \times D_{MAX} \times (1 - D_{MAX}) \times (1 - D_{MAX}) \leq 100\ \mu H \tag{20}$$

- Choose value of booster inductor:
  $L_{BOOSTER}$ = 85 µH (21)
- Inductor peak current, (A):
  $$I_{LPEAK} = \frac{V_{BUSMIN}}{L_{BOOSTER}} \times T_{SW} \times D_{MAX} = 5.34\ A \quad (22)$$
- Inductor minimum current, (A):
  I_{MIN} = 0 A (23)
- Average value of trapezoidal waveform, (A):
  I_{PA}= 0.5 × (I_{LPEAK} + I_{MIN}) = 2.66 A (24)
- DC value of trapezoidal waveform, (A):
  I_{DC} = D_{MAX} × I_{PA} = 2.54 A (25)
- RMS value of trapezoidal waveform, (A):
  $$I_{RMS} = \sqrt{[D_{MAX} \times \{(I_{LPEAK} \times I_{MIN}) + (I_{LPEAK} - I_{MIN}) \times (I_{LPEAK} - I_{MIN})\}]} = 2.98 A \quad (26)$$
- AC value of trapezoidal waveform, (A):
  $$I_{AC} = \sqrt{I_{RMS}^2 - I_{DC}^2} = 1.57 A \quad (27)$$
- Maximum peak short circuit current:
  I_{SCPK} = I $_{LPEAK}$ × 1.2 = 6.41 A (28)

3. Select Core Material 3C92

4. Determine Max Flux Density and Max Flux Swing

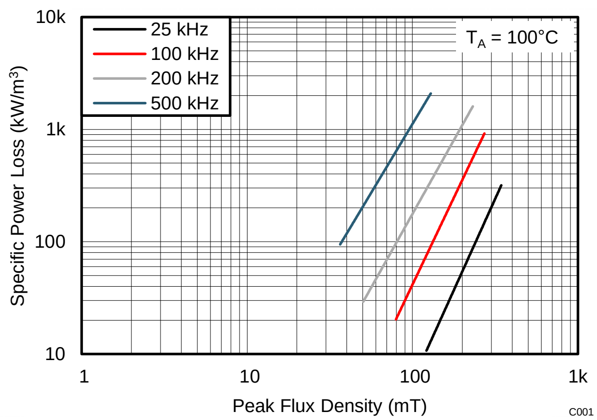


Figure 4. Specific Power Loss as a Function of Peak Flux Density with Frequency as a Parameter

- Loss Limit considered:
  $$300 \frac{mW}{cm^3} = 300 \frac{kW}{m^3} \quad (29)$$
- Peak Flux density at the loss limit from the graphs at:
  25 KHz = 0.3 T (30)
- Peak to Peak flux density swing:
  ΔB_{MAX} = 0.6 T in DCM Mode ΔB_{MAX} = B_{MAX} (31)
- BMAX = 0.28 T (32)

- Constant K1 = 0.03

  where
  - $K_1 = J_{MAX} \times K_{PRI} \times 10^{-4}$
  - J_{MAX} = Max current density
  - K_{PRI} represents the utilization of the window containing the winding. For a single winding inductor, K_{PRI} is the ratio of the total copper area to the window area Aw. For a flyback converter, K_{PRI} is the ratio of the primary winding copper cross-section area to the total area. (33)
- Area Core Product Calculation (A_P):

$$A_P = A_W \times A_E = [\frac{L_{BOOSTER}}{B_{MAX}} \times \frac{I_{SCPK}}{K_1} \times I_{FL}]^{4/3}\ cm^4 = 0.155754144\ cm^4 \tag{34}$$

  where
  - $L_{BOOSTER}$ = Booster Inductance
  - I_{SCPK} = 20% of I_{LPEAK}, A
  - I_{FL} = RMS Current, full load, A
  - B_{MAX} = Saturation limited flux density, T (35)
- Core Selected: EF25
  - Effective Volume:

    Ve = 2.99 cm^3 (36)
  - Effective Length:

    Le = 5.8 cm (37)
  - Effective Area:

    Ae = 0.52 cm^2 (38)
- Bobbin Details
  - Minimum Winding Width:

    W_W = 1.545 cm (39)
  - Minimum Winding Height:

    W_H = 0.432 cm (40)
  - Average Length of Turn:

    L_T = 5.28 cm (41)
  - Winding Area:

    $A_W = W_W \times W_H = 0.677\ cm_2$ (42)
  - Area Product:

    $A_P = A_W \times AE = 0.347\ cm^4$ (43)

5. Define R_T and Loss Limit

- Thermal resistance of core:

  R_T = 28 °C/W (44)
- Maximum temperature rise:

  ΔT = 50 °C (45)
- Power loss limit based on maximum temperature rise:

  $P_{LIM} = R_T \times \Delta T$ = 1.79 W (46)
- Core Loss Limit:

  P_C = 0.3 W (47)
- Winding Loss Limit:

  $P_W = P_{LIM} - P_C$ = 1.49 W (48)
- Preliminary core loss calculation:

  P_C = Loss Limit considered × Effective Volume = 897 mW (49)

- Maximum flux density, T:

$$\Delta B_{MAX} = B_{MAX} \times \frac{I_{LPEAK}}{I_{SCPK}} = 0.2333 \quad (50)$$

- Peak flux swing:

$$\frac{\Delta B_{MAX}}{2} = 0.1166\,T \quad (51)$$

- Core loss at peak flux swing:

< 50 mW/cm^3 (52)

- PC core loss corrected:

Core loss at peak flux swing × Effective Volume < 200 mW (53)

6. Calculate Maximum Number of Turns

$$N = \frac{\left(L_{BOOSTER} \times I_{LPEAK} \times 10^{-2}\right)}{\Delta B_{MAX} \times A_E} = 37.42 \quad (54)$$

- Actual number of turns:

N_A = 30 (55)

- Change in the flux density due to actual number of turns:

$$\Delta B_{MAX} \times \frac{N}{N_A} = 0.2910\,T \quad (56)$$

- Peak flux density swing:

0.14554 T (57)

- Core loss at Peak flux density:

< 100 mW/cm_3 (58)

- Core losses Pc actual:

Core loss at Peak flux density × V_E < 299 mW (59)

7. Air Gap Calculation

$$lg = \frac{\left(0.4 \times 3.14 \times L_{BOOSTER} \times I^2_{LPEAK}\right) \times 10^8}{A_E \times B^2_{MAX} \times 10^8} = 0.10769\,cm = 1.1\,mm \quad (60)$$

8. Calculate the Conductor Size

- Minimum winding width:

B_W = 1.545 cm (61)

- Height:

H_W = 0.432 cm (62)

- Creepage allowance:

Cma_A = 0.3 cm (63)

- Actual winding width possible:

$B_{WA} = B_W - 2 \times C_A$ = 0.945 cm (64)

- Current Density:

J_{MAX} = 450 A / cm^2 (65)

- Wire size required:

$$Conductor\ Area = \frac{RMS\ Current}{Current\ Density} = 0.006673138\ cm^2 \quad (66)$$

NOTE: For further details about DC-DC Booster Inductor L1, refer to Part Number 750342278 from Wurth Electronics listed in the Bill of Materials (BOM).

9. Switching Frequency

Switching Frequency of the DC-DC Converter is 35 KHz in order to obtain enough ON time at higher line voltages. RT and CT values are 1.33 M and 470 pF.

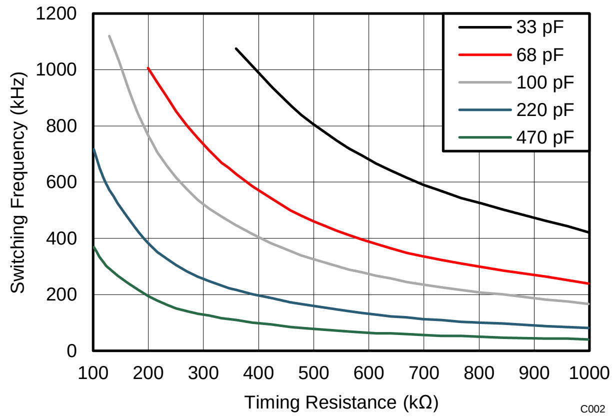


Figure 5. Frequency versus Timing Resistance

10. Output Diode Selection

- Using 80% dating on V_{OUT} for ringing on the switch node. The rectifier diode minimum reverse breakdown voltage is given by:

  $V_{PIVBDIODE} \geq 1.25 \times V_{BOOSTOUT} \geq 488$ V (67)

- The diode must have a reverse breakdown voltage greater than 500 V. The rectifier diode peak and average currents are estimated by:

  $IBD_{(avg)} = I_{BOOSTOUT} = 0.096$ A (68)

  $I_{BD(PEAK)} = I_{LPEAK} = 5.34$ A (69)

- The power dissipation in the diode is estimated by:

  $P_{BDiode} = {}_{IBD(avg)} \times V_F = 0.067$ W (70)

Table 1. Output Diode Selection

Part Number	MUR460
Type of Diode	Ultrafast
PIV	600 V
IF	4 A
Surge Current Rating	150 A

11. Output Capacitor Selection

$$C_{OUT} = \frac{(8 \times I_{BOOSTOUT} \times D_{MAX})}{(V_{BOOSTOUT\ RIPPLE} \times F_{SW})} \tag{71}$$

$V_{BOOSTOUT}$ RIPPLE = 0.5 V (72)

C_{OUT} with 20% tolerance = 50 µF (73)

$$ESR\,C_{OUT} = \frac{(7 \times V_{BOOSTOUTRIPPLE})}{(8 \times (I_{LPEAK-}I_{BOOSTOUT})} = 0.083\ \Omega \tag{74}$$

Table 2. Output Capacitor Selection

SELECTED C_{OUT}	68	µF	450	V
PART NUMBER	EKXG451ELL680MMN3S		United Chemicon	

12. Current Sense and Current Limit

- The load current old is set by the proper choice of R_{ISNS}. If the converter is operating in discontinuous mode, the current sense resistor is given by:

$$R_{ISNS} = \frac{F_{SW} \times L_{BOOSTER} \times V_{ISNS(OC)}}{\sqrt{(2 \times L_{BOOSTER} \times F_{SW} \times I_{OUT(OC)} \times (V_{OUT} + V_D - V_{IN})}} \quad (75)$$

$V_{ISNS(OC)} = 0.15$ V (76)

R_{ISNS} is approxmately 30 mΩ (77)

- Power Dissipation in the current sense resistor:

PISNS = I^2_{RMS} × RISNS × D_{MAX} (78)

An approximately 1-W resistor is chosen

13. Soft Start Capacitor

The capacitor on the SS terminal C_{SS} also plays a role in overcurrent functionality. The design uses the capacitor as the timer between restart attempts. The soft-start time must be long enough so that the converter can start without entering an overcurrent state. Because the overcurrent state is triggered by sensing the peak voltage on the ISNS terminal, the peak voltage must be kept below the overcurrent threshold voltage. The voltage on the ISNS terminal is a function of the load current of the converter, the rate of rise of the output voltage and output capacitance, and the current sensing resistor. The total output current that must be supported by the converter is the sum of the charging current required by the output capacitor plus any external load that must be supplied during start up.

The soft start capacitor is selected based on following equations:

$$C_{SS} = \frac{t_{SS}}{\left[R_{SS} \times In\left(\frac{V_{BP} - V_{SS(OFST)}}{V_{BP} - \left(V_{SS(OFST)} + V_{FB}\right)} \right) \right]}$$

$$t_{SS} > C_{OUT} \times \frac{V_{OUT}}{\left(I_{OUT(0C)} - I_{EXT}\right)} \quad (79)$$

where

- $I_{C(Chg)}$ is the output capacitor charging current in A
- C_{OUT} is the total output capacitance in F
- V_{OUT} is the output voltage in V
- t_{SS} is the soft start time
- $I_{OUT(OC)}$ is the desired overcurrent trip point in A
- I_{EXT} is any external load current in A
- $R_{SS(chg)}$ is the SS charging resistance in Ω, typically 500 kΩ
- C_{SS} is the value of the capacitor on the SS terminal, in F
- V_{BP} is the value of the voltage on BP terminal, in V
- $V_{SS(ofst)}$ is the approximate level shift from the SS terminal to the error amplifier (approximately 700 mV)
- V_{FB} is the error amplifier reference voltage, 700 mV typical
- Considering I_{EXT} = 0.10 A and $I_{OUT(OC)}$ = 0.12A, t_{SS} is 1.37 seconds and C_{SS} = 22 µF (80)

4.3 Flyback Converter Design Using UCC28600

4.3.1 Downstream Converter

The downstream converter is designed to work in quasi-resonant flyback mode with following specification at the end of power supply stream:

1. Working input voltage range: 100 to 400-V DC
2. Output voltages
   - 12 V, 2 A
   - –12 V, 0.25 A
   - Isolated supply 6.75 V, 0.45 A
   - Total output voltage 30 W

The design uses quasi-resonant mode topology for reduced EMI and low switching losses for higher power conversion efficiency, compared to a conventional hard switched converter with fixed switching frequency.

The design uses TI controller UCC28600 for its quasi-resonant flyback controller. The UCC28600 device is a pulse width modulation (PWM) controller with advanced energy features. The UCC28600 design meets stringent worldwide energy-efficiency requirements along with high level protection. The UCC28600 device incorporates frequency foldback and green-mode operation to reduce the operation frequency at both light load and no load operations.

4.3.2 UCC28600 Features

- Green-mode controller with advanced energy saving features
- Quasi-resonant mode operation for reduced EMI and low switching losses (low voltage switching)
- Low standby current for system no-load power consumption
- Programmable overvoltage protection, line and load
- Internal overtemperature protection
- Current-limit protection
  - Cycle-by-cycle power limit
  - Primary-side overcurrent hiccup restart mode
- 1-A sink truedrive, –0.75-A source gate drive output
- Programmable soft-start
- Green mode status terminal (PFC disable function)

The design calculator provides a user-interactive iterative process for selecting recommended component values for an optimal design (see SLVC104).

Component calculations are based on the following schematics as shown in Figure 6.

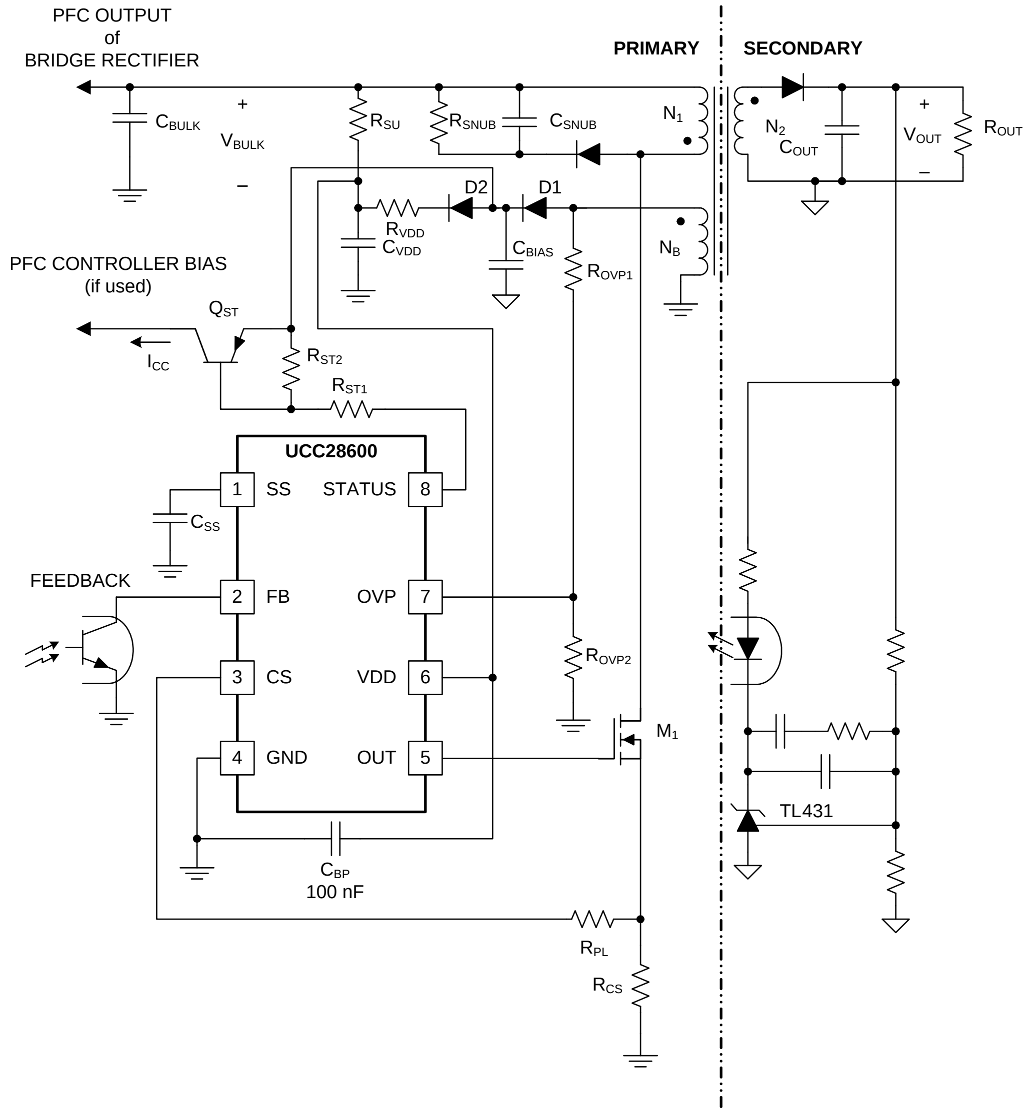


Figure 6. UCC28600 Terminal Schematic

4.3.3 Magnetics Calculation for Booster Inductor

The following calculations are for the magnetics calculation for the booster inductor, based on the application note, SLUP127:

1. Booster Design Parameters

- DC Input voltage, V:

$$V_{INDCMIN} = 90 \tag{81}$$

- DC Input voltage, V:

$$V_{INDCMAX} = 355 \tag{82}$$

- Output voltage-01, V:

$$V_{01} = 12 \tag{83}$$

- Output Load-01, A:

$$I_{01} = 2.0\ A \tag{84}$$

- Output voltage-02, V:

V_{02} = –12 (85)

- Output Load-02, A :
  I_{02} = 0.250 A (86)
- Output voltage-03, V:
  V_{03} = 6.75 V (87)
- Output Load-03, A:
  I_{03} = 0.450 A (88)
- Total Output Load, W:
  $$P_{SLOAD} = V_{01} \times I_{01} + V_{02} \times I_{02} + V_{03} \times I_{03} = \sim 30\,W \quad (89)$$

2. Preliminary Calculation

- Efficiency of Flyback Converter:
  τ2 = 0.8 (90)
- Primary Input Power, W:
  $$P_{INP} = \frac{P_{SLOAD}}{\tau_2} = 39.23\,W \quad (91)$$
- Primary Duty Cycle:
  D_P = 0.49 (92)
- Secondary Duty Cycle:
  D_S = 0.51 (93)
- Turns Ratio for secondary winding V_{01}, V_{02}:
  $$N = \frac{V_{INDCMIN}}{V_{01} + V_D} \times \frac{D_P}{1 - D_P} = 6.86 \quad (94)$$
- Actual Turn Ratio:
  N_A = 7 (95)
- Turn Ratio for Isolated Winding:
  V_{03} = 11.6→12 (96)
- Actual Duty Cycle:
  $$D_{PA} = \frac{(V_{01} + V_D) \times N_A}{V_{INDCMIN} + (V_{01} + V_D) \times N_A} = 0.495 \quad (97)$$
- D_{SA}:
  1 - D_{PA} = 0.51 (98)
- Current Calculation (Secondary Peak Current):
  $$I_{SCPK} = 2 \times \frac{I_{SDC}}{D_{SA}}$$
  where
  - I_{SDC} = Output Current I_0
    – Secondary-01 Peak Current I_{01PK} = 7.92 A
    – Secondary-02 Peak Current I_{02PK} = 0.99 A
    – Secondary-03 Peak Current I_{03PK} = 2.48 A (99)
- Secondary RMS Current:
  $$I_{SRMS} = \sqrt{D_{SA} \times \frac{I_{SCPK}^2}{3}}$$
  where
  - I_{SPK} is the respective secondary peak current I_{0PK}
  - Secondary-01 RMS Current: I_{01RMS} = 3.25 A
  - Secondary-02 RMS Current: I_{02RMS} = 0.41 A
  - Secondary-03 RMS Current: I_{03RMS} = 1.02 A (100)
- Secondary AC Current:

$$I_{AC} = \sqrt{\left(I_{RMS}^2 - I_{DC}^2\right)}$$

where

- I_{RMS} and I_{DC} are the RMS and DC Output current of the secondary winding
- Secondary-01 AC Current: I_{01AC} = 2.56 A
- Secondary-02 AC Current: I_{02AC} = 0.41 A
- Secondary-03 AC Current: I_{03AC} = 0.94 A (101)

- Primary Average Current:

$$I_{PAVG} = \frac{P_{INP}}{V_{INDCMIN}} = 0.44\ A \quad (102)$$

- Primary Peak Current:

$$I_{PPEAK} = 2 \times \frac{I_{PAVG}}{D_{PA}} = 1.85\ A \quad (103)$$

- Primary Inductance Required:

$$L_P = V_{INDCMIN} \times \frac{\Delta t}{\Delta I} = V_{INDCMIN} \times T_{SW} \times \frac{D_{PA}}{I_{PPEAK}} = 480\ \mu H \quad (104)$$

- Inductor Mininum Current, A

I_{MIN} = 0 A (105)

- Average Value of Trapezoidal Waveform, A:

$$I_{PA} = 0.5 \times \left(I_{PPEAK} + I_{MIN}\right) = 0.93\ A \quad (106)$$

- DC Value of Trapezoidal waveform, A:

$$I_{DC} = D_{MAX} \times I_{PA} = 0.464A \quad (107)$$

- RMS value of Trapezoidal Waveform, A:

$$I_{RMS} = \sqrt{[D_{MAX} \times \{(I_{PPEAK} \times I_{MIN}) + (I_{PPEAK} - I_{MIN}) \times (I_{PPEAK} - I_{MIN})\}]} = 0.75A \quad (108)$$

- AC Value of Trapezoidal Waveform, A:

$$I_{AC} = \sqrt{I_{RMS}^2 - I_{DC}^2} = 0.60A \quad (109)$$

- Max Peak Primary Short Circuit Current:

$$I_{PSCPK} = I_{PPEAK} \times 1.1 = 2.0\ A \quad (110)$$

3. Select Core Material TP4A

4. Determine Max Flux Density and Max Flux Swing

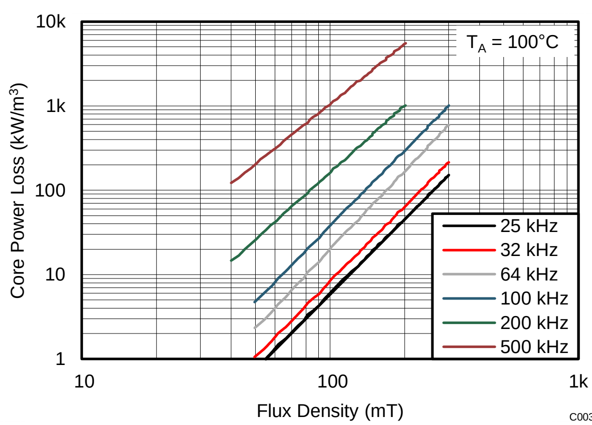


Figure 7. Flux Density (mT) versus Core Power Loss (kW/m^3)

- Loss Limit considered:

$$300 \frac{mW}{cm^3} = 300 \frac{kW}{m^3} \quad (111)$$

- Peak Flux density at the loss limit from the graphs at:
  100 KHz = 0.11 T (considered) (112)
- Peak to Peak flux density swing:
  ΔB_{MAX} = 0.22 T in DCM Mode $\Delta B_{MAX} = B_{MAX}$ (113)
- B_{MAX} = 0.22 T (114)
- Constant K1 = 0.085

  where
  - $K_1 = J_{MAX} \times K_{PRI} \times 10^{-4}$
  - J_{MAX} = Max current density
  - K_{PRI} represents the utilization of the window containing the winding. For a single winding inductor, K_{PRI} is the ratio of the total copper area to the window area Aw. For a flyback converter, K_{PRI} is the ratio of the primary winding copper cross-section area to the total area. (115)
- Area Core Product Calculation (A_P):

$$A_P = A_W \times A_E = [\frac{L_P}{B_{MAX}} \times \frac{I_{SCPK}}{K_1} \times I_{FL}]^{4/3} cm^4 = 0.288952\ cm^4 \quad (116)$$

  where
  - L_{PA} = Primary Inductance
  - I_{SCPK} = 10% of I_{LPEAK}, A
  - I_{FL} = RMS Current, full load, A
  - B_{MAX} = Saturation limited flux density, T (117)
- Core Selected: ER28/14
  - Effective Volume:
    Ve = 5.2544 cm^3 (118)
  - Effective Length:
    Le = 6.4 cm (119)
  - Effective Area:
    Ae = 0.821 cm^2 (120)
- Bobbin Details
  - Minimum Winding Width:
    W_W = 1.661 cm (121)
  - Minimum Winding Height:
    W_H = 0.439 cm (122)
  - Average Length of Turn:
    L_T = 5.28 cm (123)
  - Winding Area:
    $A_W = B_W \times H_W$= 0.729179 cm^2 (124)
  - Area Product:
    $A_P = A_W \times A_E$ = 0.598656 cm^4 (125)
- Mean Length per Turn:
  MLT = 3.83 cm (126)

5. Define R_T and Loss Limit

- Thermal resistance of core:
  R_T = 28.75 °C/W (127)
- Maximum temperature rise:
  ΔT = 50 °C (128)
- $P_{limit:}$
  °CRise/R_T = 1.73913 W (129)
- Preliminary core loss calculation:

P_C = Loss Limit considered × Effective Volume = 525.44 mW (130)

6. Calculate Number of Turns

$$N = \frac{\left(L_P \times I_{PPEAK} \times 10^{-2}\right)}{\Delta B_{MAX} \times A_E} = 49.32 \tag{131}$$

- Chosen number of primary turns:
  N_{PA} = 49
- Calculated number of secondary turns:
  N_{S01} = 7
- Calculated number of secondary turns:
  N_{S02} = 7
- Chosen number of secondary turns:
  N_{S02} = 8
- Calculated number of isolated secondary turns:
  N_{S03} = 4.3 → 4
- Change in the ΔB_{MAX} due to the round off of:

$$N_P = \Delta B_{MAX} \times \frac{N}{N_A} = 0.22\,T \tag{132}$$

- Peak flux density: 0.11 T
- Actual core loss will be less than 525.44 mW, as there is no considerable change in the flux density

7. Air Gap Calculation

$$lg = \frac{\left(0.4 \times 3.14 \times L_p \times I_{PPEAK}^2\right) \times 10^8}{A_E \times B_{MAX}^2 \times 10^8} = 0.0521968\ cm = 0.52197\ mm \tag{133}$$

8. Calculate the Conductor Size and Winding Resistance

- Minimum winding width:
  B_W = 1.661 cm
- Height:
  H_W = 0.439 cm
- Creepage allowance:
  C_A = 0.3 cm
- Actual winding width possible:
  $B_{WA} = B_W - 2 \times C_A$ = 1.061 cm
- Current density:
  J_{MAX} = 450 A/cm^2
- Wire size required:

$$Conductor\ Area = \frac{RMS\ Current}{Current\ Denity} \tag{134}$$

- Wire size for output-01:
  W_{01} = 0.72 mm^2
- Wire size for output-02:
  W_{02} = 0.09 mm^2
- Wire size for output-03:
  W_{03} = 0.14 mm^2
- Wire size for primary W_P:
  W_P = 0.16 mm

	W1	W2	W3	W4	W5
Requested Turns	49	8	7	8	4
Turns Ratio	—	6.1	7	6.1	12.3

The total number of terminals required is 12. However, since the required 12 terminal bobbin is not available, the design uses a 10 terminal Bobbin. Two windings points are floating in the Wurth transformer. For further details, refer to the Wurth part number given in the Bill of Materials (BOM).

9. PIV Rating for Secondary Turn's Diode

$$PIV_{SECONDARY\ DIODE} = \frac{V_{INDCMAX}}{TURN\ RATIO_S} + V_0 \quad (135)$$

The following are PIV Values using the PIV Rating for Secondary Turn's Diode equation:

- PIV V_{01} = 68.31428571 V
- PIV V_{02} = 68.31428571 V
- PIV V_{03} = 41.05 V
- Secondary Peak Current I_{01PK} = 7.92 A
- Secondary Peak Current I_{02PK} = 0.99 A
- Secondary Peak Current I_{03PK} = 2.48 A
- Secondary RMS Current I_{01RMS} = 3.25 A
- Secondary RMS Current I_{02RMS} = 0.41 A
- Secondary RMS Current I_{03RMS} = 1.02 A

Based on Secondary Peak current and RMS current , the design uses the following Secondary Rectifiers.

Table 3. Secondary Rectifiers

RECTIFIER DIODE	V_{01}	V_{02}	V_{03}	SYMBOL	UNIT
Diode	SS8PH10	ES3D	CDBB280-G		
Maximum repetitive peak reverse voltage	100	200	80	V	V_{RRM}
Maximum average forward rectified current	8	3	2	A	$I_{F(AV)}$
Peak forward surge current 10 ms single half sine-wave superimposed on rated load	150	100	50	A	I_{FSM}

10. Primary MOSFET Selection

- Stress on MOSFET due to reflected voltage:

$$V_{MOSFETREF} = V_{DCINMAX} + V_{OUT} \times TurnRatio_s = \sim 477\,V \quad (136)$$

- Stress due to leakage inductance:

$$V_{MOSFETLKG} = Leakage\,Inductance_{Primary} \times \frac{I_{PPEAK}}{DUTYCYCLE_{MAX} \times T_{SW}} \quad (137)$$

- Considering leakage inductance to be 2% of Primary inductance value:

  $V_{MOSFETLKG}$ = 91.8 V

  $V_{MOSFETSTRESS} = V_{MOSFETREF} + V_{MOSFETLKG}$

  $V_{MOSFETSTRSS}$ = 568.3

- Peak Current:

  $I_{PEAKMOSFET} = I_{PPEAK}$ = 2 A

- RMS Current:

  $I_{RMSMOSFET} = I_{PRMS}$ = 0.7 A

Table 4. MOSFET Rating (AOTF4S60)

PARAMETER	RATING	UNITS	SYMBOL
Drain-Source Voltage	600	V	V_{DS}
Continuous Drain Current at 25C	4	A	I_D
Continuous Drain Current at 100C	3.7	A	I_D
Pulsed Drain Current	16	A	I_{DM}
RDS(On) Max	0.9	Ω	

5 Test Setup

Input conditions:

- DC input: 15 to 250-V DC power supply with current capability of at least 4 A.
- AC input: AC source capable of providing 70 to 280-V AC at 2-A current capability.

Output conditions:

- Electronic load in CC mode or power resistors.

Equipment Used:

1. Programmable DC Voltage source 0 to 250 V, 5 A
2. Programmable AC Voltage source 0 to 275 V, 5 A
3. Single phase AC power analyzer
4. Digital Oscilloscope
5. Multimeter
6. Electronic loads and Power resistors

Procedure:

1. Connect the appropriate source to the input terminals of the PSU.
2. Connect outputs to electronic loads.
3. Turn on the source with no load on all outputs.
4. Increase the load on main output (12 V) to approximately 2 A.
5. Increase the load on auxiliary outputs to their full loads.

6 Test Results

6.1 Functional – Output Voltages at Different Nominal Voltages

Table 5. DC Input

V_{IN}, V DC	P_{IN}, W	$V_{01\ +\ 12\ V}$, V	I_{01}, A	$V_{02\ –\ 12\ V}$, V	I_{02}, A	$V_{03\ +\ 6.75\ V}$, V	I_{03}, A	P_O, W	EFFICIENCY
20	46.8	12.04	2	–11.99	0.25	6.89	0.450	30	63.75
24.0	46.2	12.03	2	–11.98	0.25	6.88	0.450	30	64.48
110	39.8	12.04	2	–11.99	0.25	6.89	0.450	30	74.92
220	38.5	12	2	–11.99	0.25	6.89	0.450	30	77.28

Table 6. AC Input

V_{IN},V AC	P_{IN}, W	$V_{01\ +\ 12\ V}$, V	I_{01}, A	$V_{02\ –\ 12\ V}$, V	I_{02}, A	$V_{03\ +\ 6.75\ V}$, V	I_{03}, A	P_O, W	EFFICIENCY
80	42.33	12.04	2	–11.96	0.25	6.88	0.450	30	70.45
220	39.22	12.04	2	–11.99	0.25	6.88	0.450	30	76.06
250	38.37	12.04	2	–11.98	0.25	6.89	0.450	30	77.75

6.2 Line Regulation

Table 7. Line Regulation DC Supply

V_{IN}, V DC	I_{IN}, A	P_{IN}, W	$V_{01 + 12 V}$, V	I_{01}, A	$V_{02 - 12 V}$, V	I_{02}, A	$V_{03 + 6.75 V}$, V	I_{03}, A	P_O, W	EFFICIENCY
20	2.34	46.8	12.04	2	–11.99	0.25	6.89	0.450	30	63.75
20.2	2.34	47.3	12.04	2	–11.99	0.25	6.89	0.450	30	63.12
22.0	2.115	46.5	12.04	2	–11.98	0.25	6.89	0.450	30	64.11
24.0	1.926	46.2	12.03	2	–11.98	0.25	6.88	0.450	30	64.48
48	0.882	42.3	12.04	2	–11.99	0.25	6.89	0.450	30	70.47
72	0.567	40.8	12.04	2	–11.99	0.25	6.89	0.450	30	73.08
110	0.362	39.8	12.04	2	–11.99	0.25	6.89	0.450	30	74.92
150	0.261	39.2	12.04	2	–12	0.25	6.89	0.450	30	76.21
220	0.175	38.5	12	2	–11.99	0.25	6.89	0.450	30	77.28
250	0.154	38.5	12.04	2	–11.98	0.25	6.89	0.450	30	77.48

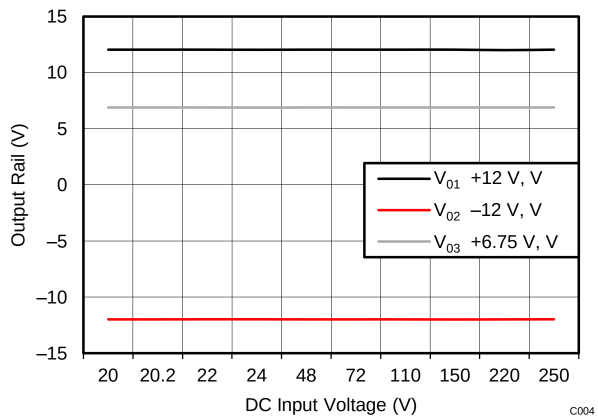


Figure 8. Output Rail (V) versus DC Input Voltage (V)

Table 8. Line Regulation AC Supply

V_{IN}, V AC	P_{IN}, W	$V_{01 + 12V}$, V	I_{01}, A	$V_{02 - 12V}$, V	I_{02}, A	$V_{03 + 6.75 V}$, V	I_{03}, A	P_O, W	EFFICIENCY
80	42.33	12.04	2	–11.96	0.25	6.88	0.45	30	70.45
110	40.91	12.04	2	–11.98	0.25	6.88	0.45	30	72.91
220	39.22	12.04	2	–11.99	0.25	6.88	0.45	30	76.06
250	38.37	12.04	2	–11.98	0.25	6.89	0.45	30	77.75
276	38	12.04	2	–11.98	0.25	6.89	0.45	30	78.5

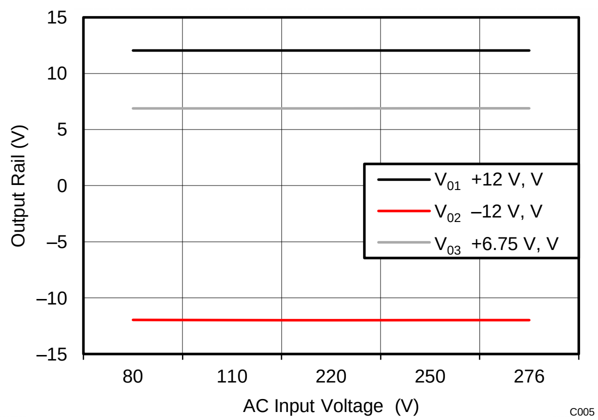


Figure 9. Output Rail (V) versus AC Input voltage (V)

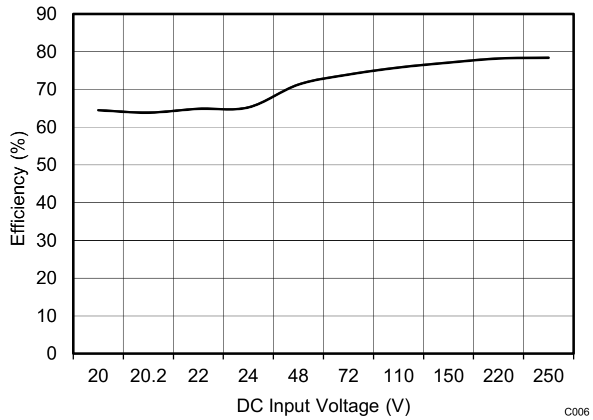


Figure 10. Efficiency (%) versus DC Input Voltage (V)

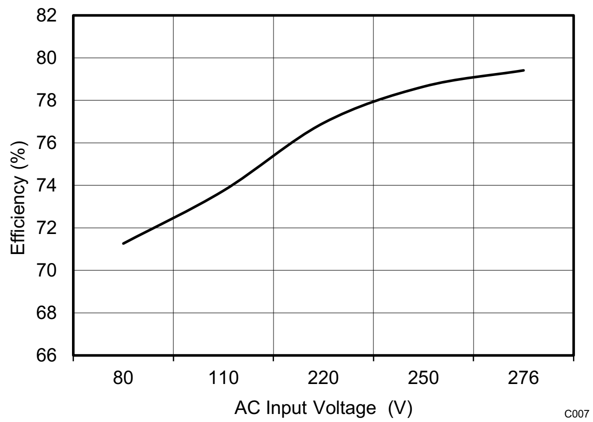


Figure 11. Efficiency (%) versus AC Input Voltage (V)

6.3 Load Regulation

Load is varied from 100% to 10% for all the loads together.

Table 9. Load Regulation

% LOAD	I_{01}, A RATED	I_{01}, A ACTUAL	$V_{01\ +\ 12\ V}$, V	I_{02}, A RATED	I_{02}, A ACTUAL	$V_{02\ -\ 12\ V}$, V	I_{03}, A RATED	I_{03}, A ACTUAL	$V_{03\ +\ 6.75\ V}$, V
100%	2	2	12.03	0.25	0.25	–11.97	0.45	0.45	6.88
80%	2	1.6	12.05	0.25	0.2	–11.96	0.45	0.36	6.89
60%	2	1.2	12.06	0.25	0.15	–11.95	0.45	0.27	6.91
40%	2	0.8	12.08	0.25	0.1	–11.94	0.45	0.18	6.93
20%	2	0.4	12.09	0.25	0.05	–11.93	0.45	0.09	6.87
10%	2	0.2	12.1	0.25	0.025	–11.92	0.45	0.045	6.87

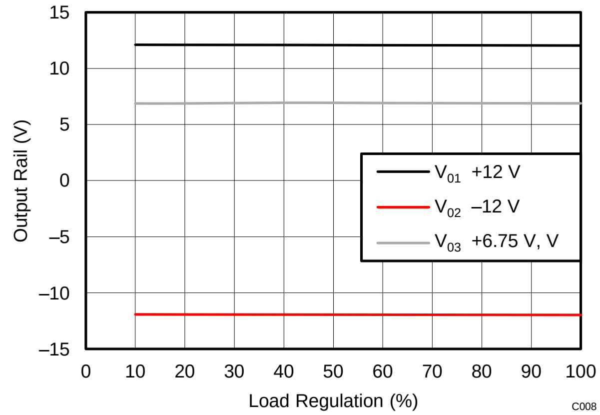


Figure 12. Output Rail (V) versus Load Regulation (%)

Performance of the power supply when one winding load is varied and other winding loads are kept constant at full load is shown in the following table.

Table 10. Variation in V_{01} and V_{02} at 24 V DC

	I_{01}, A	$V_{01\ +\ 12\ V}$, V	% REGULATION	$V_{02\ –\ 12\ V}$, V	% REGULATION	$V_{03\ +\ 6.75\ V}$, V	% REGULATION
Variation in V_{01} load at 24- V DC	2	12.03	< 1%	–11.98	< 1%	6.88	< 4%
	1.75	12.04		–11.94		6.85	
	1.5	12.05		–11.93		6.82	
	1.25	12.06		–11.94		6.79	
	1	12.07		–11.98		6.77	
	0.75	12.08		–11.93		6.72	
	0.5	12.09		–11.92		6.64	
Variation in V_{02} load at 24 V DC	I_{02}, A	$V_{01\ +\ 12\ V}$, V	% REGULATION	$V_{02\ –\ 12\ V}$, V	% REGULATION	$V_{03\ +\ 6.75\ V}$, V	% REGULATION
	0.25	12.03	< 1%	–11.99	< 2%	6.89	< 1%
	0.225	12.04		–11.88		6.88	
	0.2	12.04		–11.86		6.89	
	0.175	12.04		–11.95		6.89	
	0.15	12.04		–12.06		6.89	
	0.125	12.04		–12.18		6.89	
	0.1	12.04		–12.18		6.9	
	0.075	12.04		–12.18		6.9	
	0.05	12.04		–12.19		6.9	

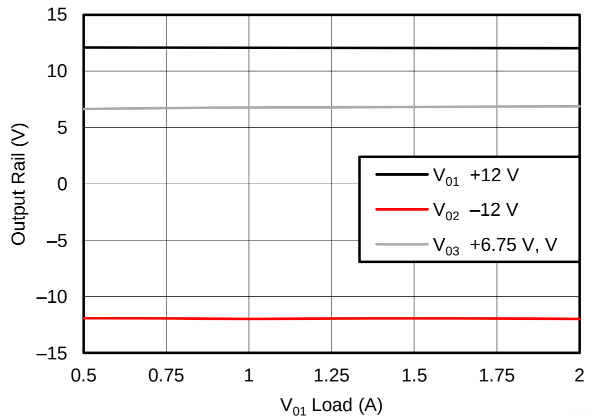


Figure 13. Output Rail (V) versus V_{01} Load (A)

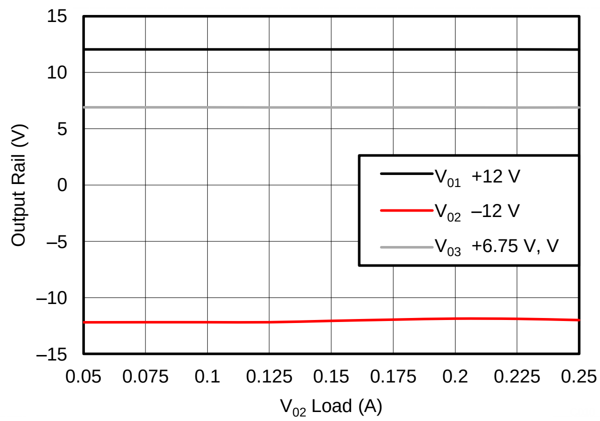


Figure 14. Output Rail (V) versus V_{02} Load (A)

6.4 Waveforms at Various Test Points as Indicated

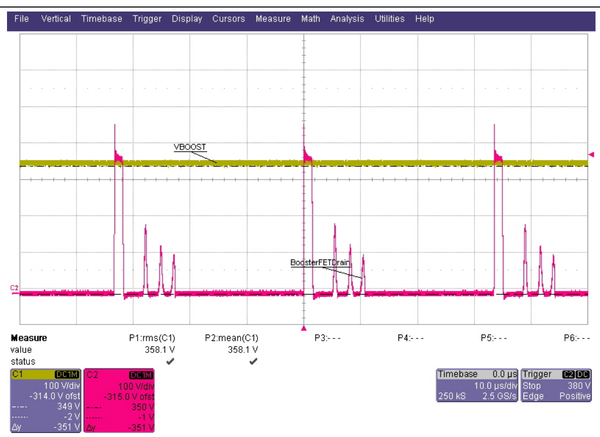


Figure 15. CH1: V_{BOOST} CH2 : Booster FET Drain 24-V DC

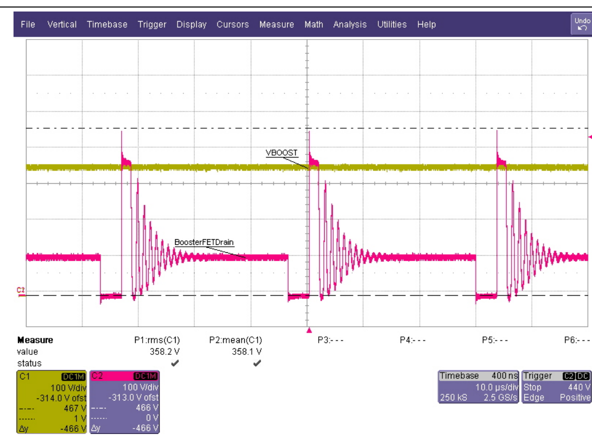


Figure 16. CH1: V_{BOOST} CH2 : Booster FET Drain 110-V DC

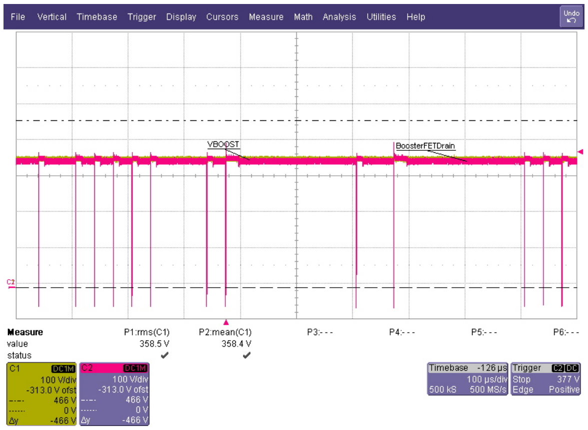


Figure 17. CH1: V_{BOOST} CH2 : Booster FET Drain 350-V DC

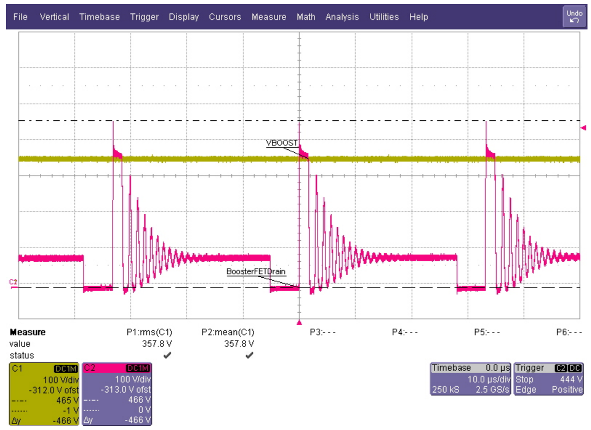


Figure 18. CH1: V_{BOOST} CH2 : Booster FET Drain 80-V AC

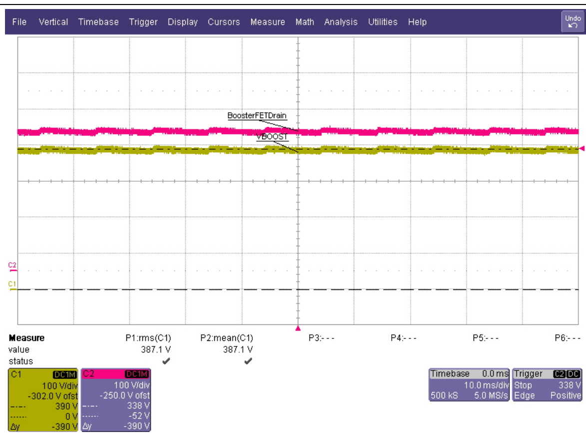


Figure 19. CH1: V_{BOOST} CH2: Booster FET Drain 272-V AC

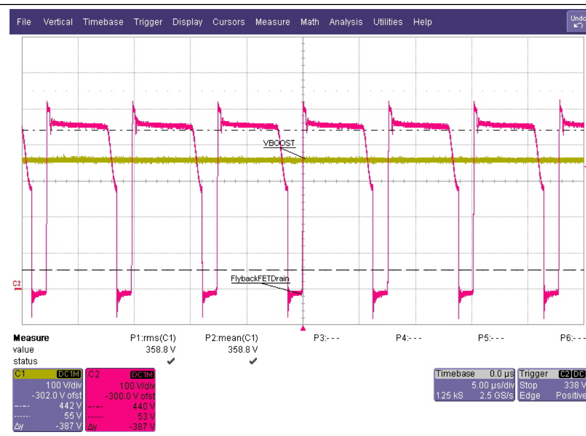


Figure 20. CH1: V_{BOOST} CH2: Flyback MOSFET Drain 240-V AC

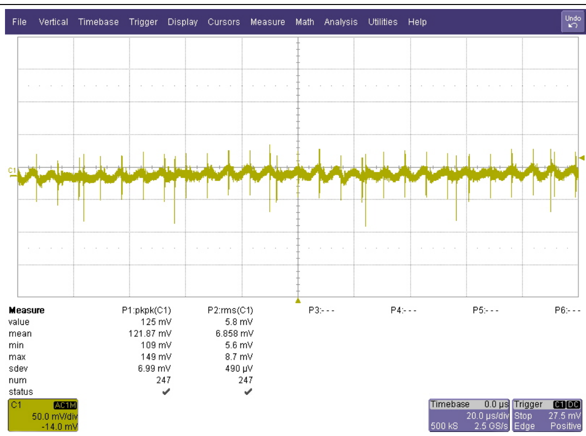


Figure 21. CH1: Ripple 12 V

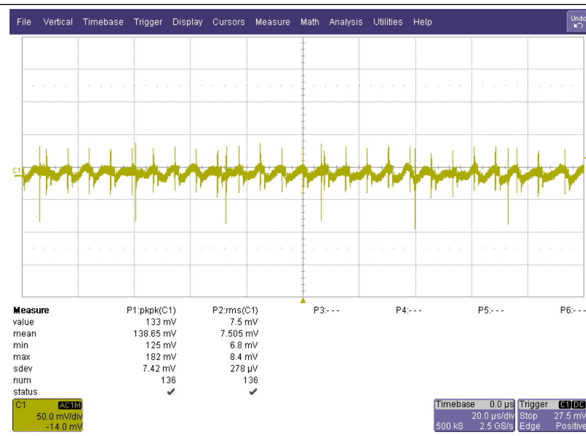


Figure 22. CH1: Ripple –12 V

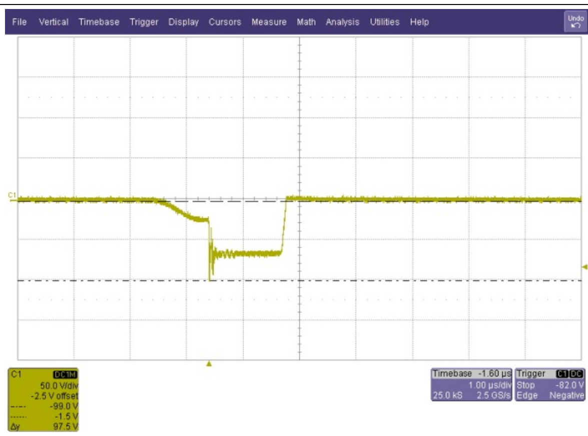


Figure 23. CH1: Maximum Voltage Across 12 V Output Diode

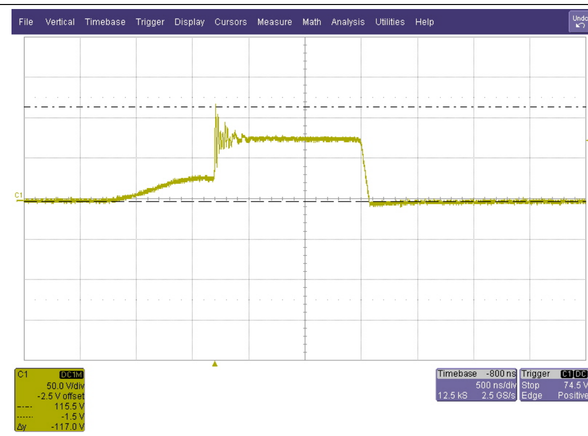


Figure 24. CH1: Maximum Voltage Across -12V Output Diode

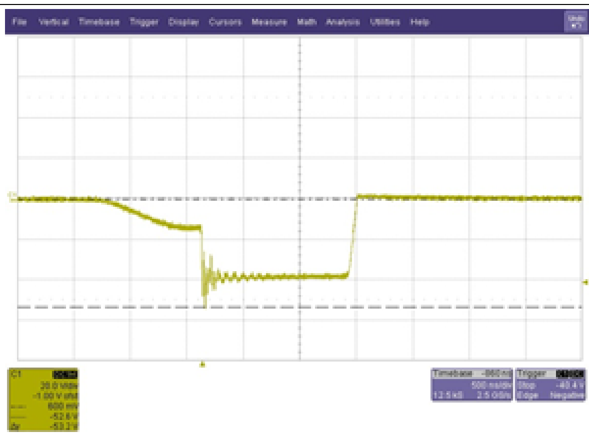


Figure 25. CH1: Maximum Voltage Across –6.75 V Output Diode

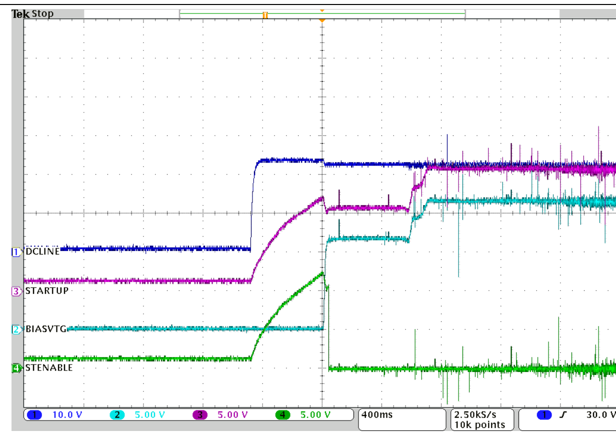


Figure 26. Start Up Circuit Operation at 24-V Full Load

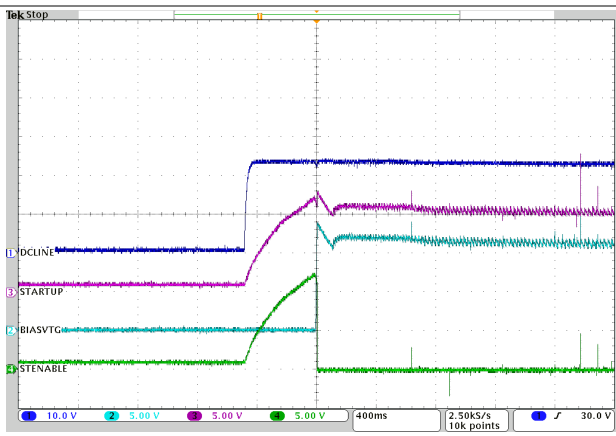


Figure 27. Start Up Circuit Operation at 24-V No Load

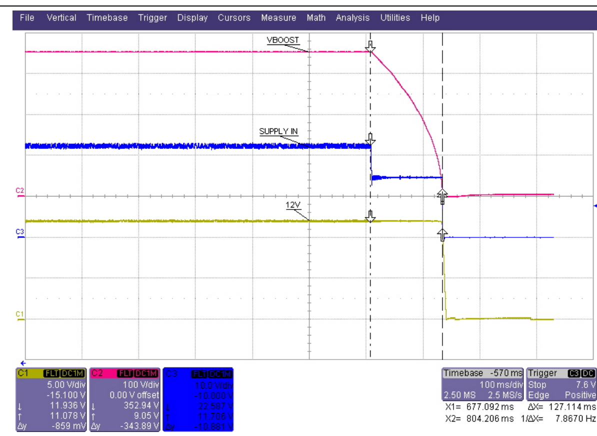


Figure 28. Power Failure to 12V → 0 V Time at 24 V with Full Load

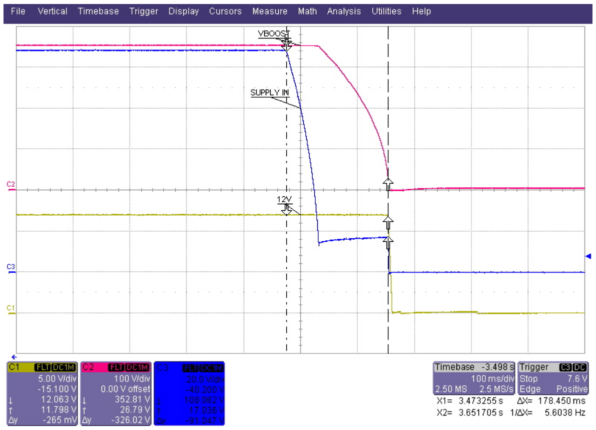


Figure 29. Power Failure to 12V → 0 V Time at 110 V with Full Load

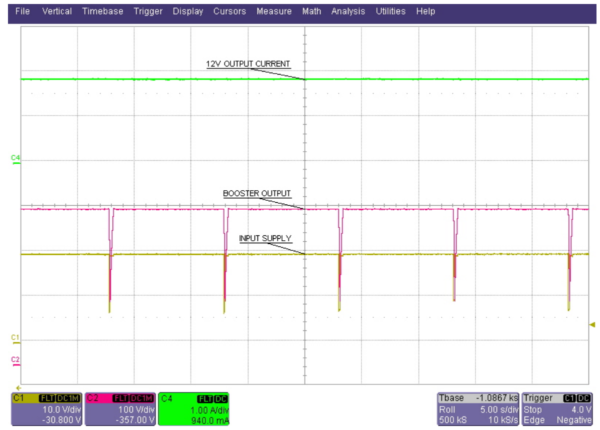


Figure 30. Voltage Interruption 24-V DC

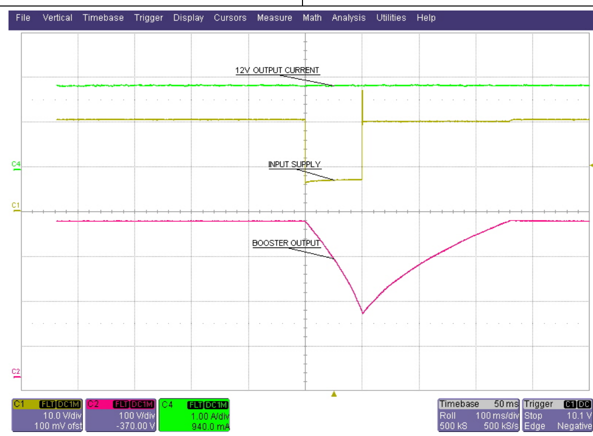


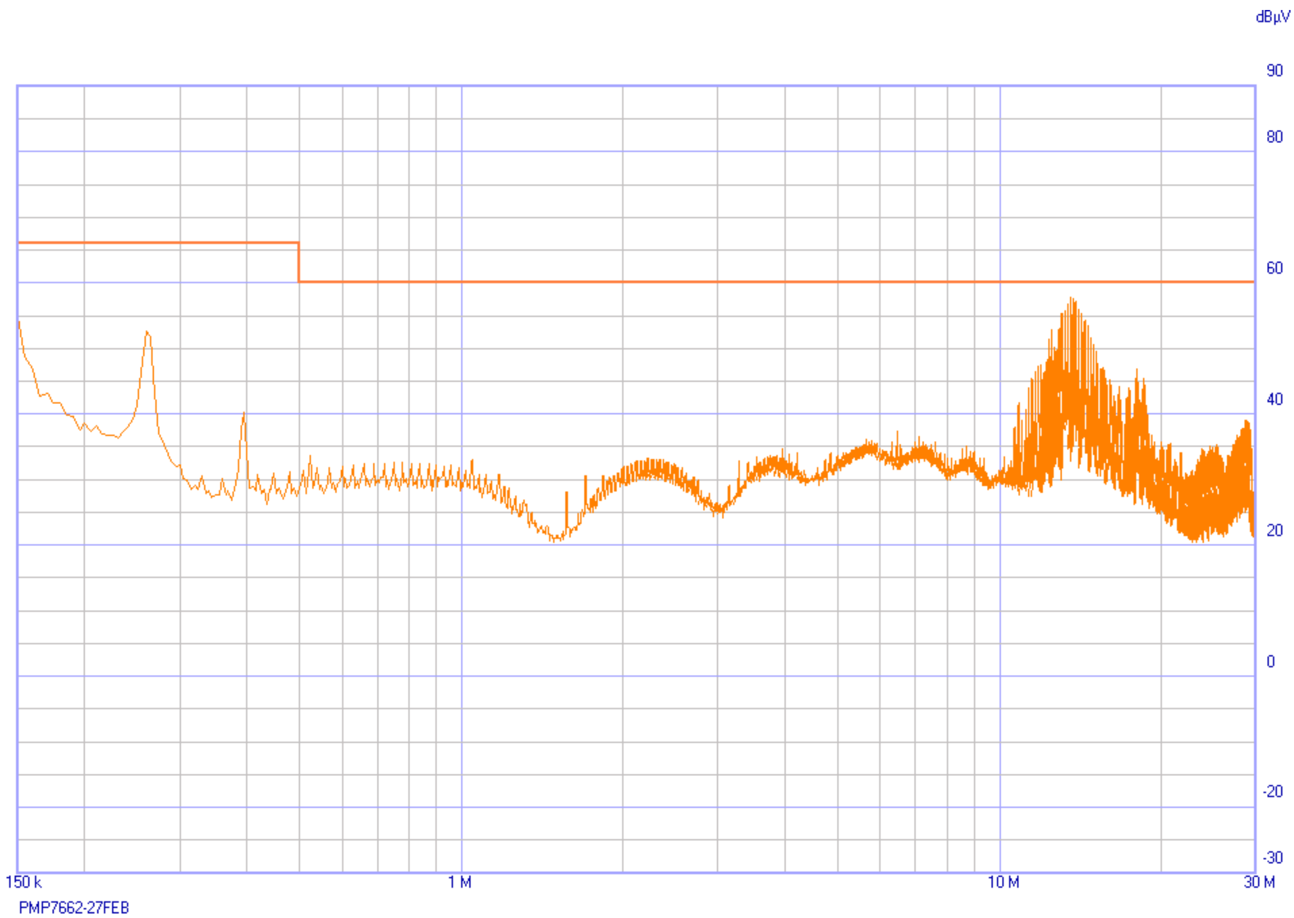
Figure 31. Voltage Interruption 24-V DC TS

6.5 EMI

Texas Instruments tested this board for compliance using the following test:

Conducted Emission test as per EN 55011 CISPR 11, Group 1, Class A.

Result: Pass in Average.

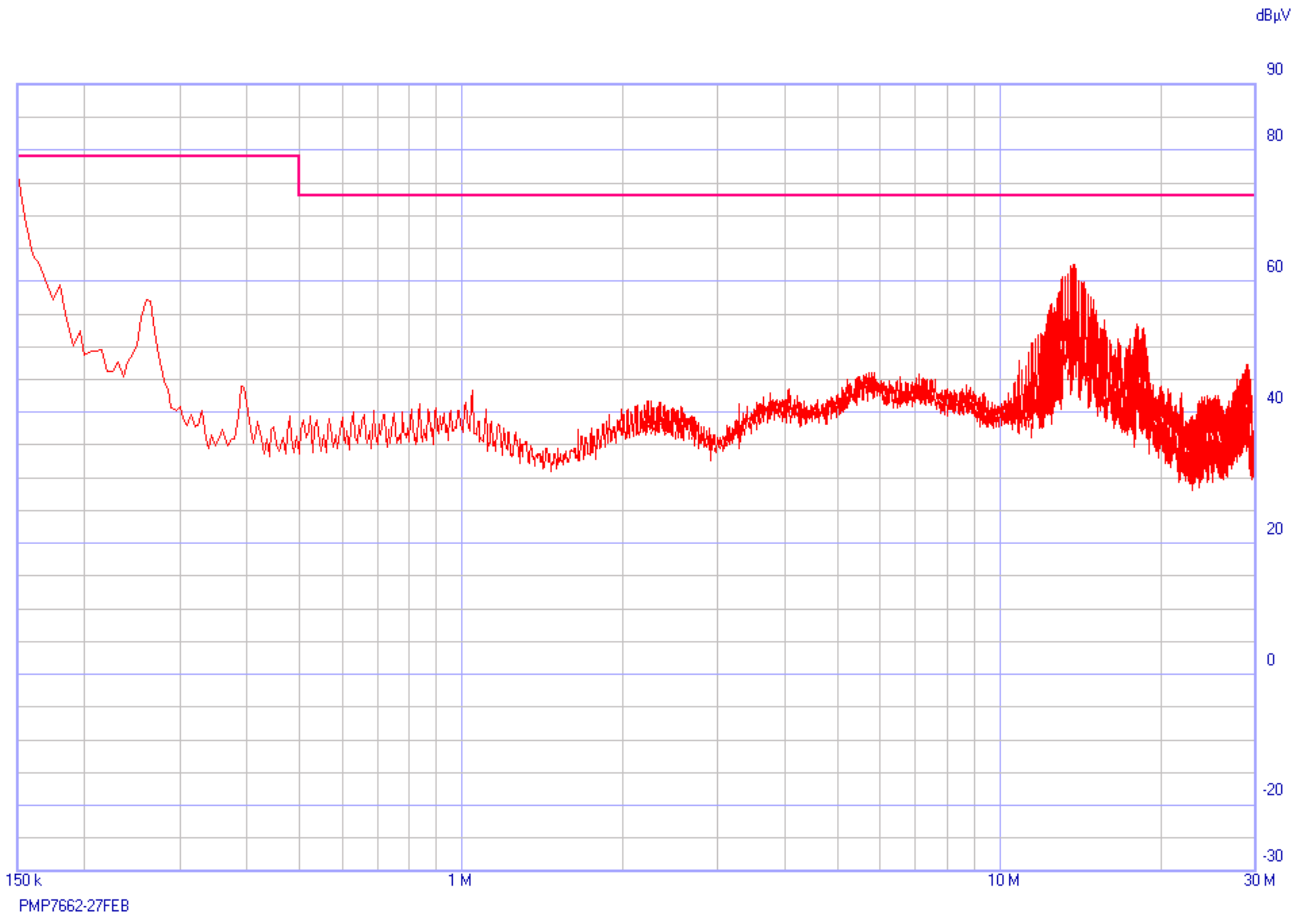


	Start [MHz]	Stop [MHz]	Step	Detector	Hold Time	RBW	Min Att	Pre Amp	Pre Sel	Prompt start	Ancillary
1	0.15	30	AUTO (5 kHz)	PA 55011aqp 55011aav	20 ms	9 kHz	10	OFF	OFF	...	L1, L2

Pulse Limiter ON
Ancillary = L2 7010
Limits:
55011aav

Avg

Figure 32. Average Test Result at 230-V AC



	Start [MHz]	Stop [MHz]	Step	Detector	Hold Time	RBW	Min Att	Pre Amp	Pre Sel	Prompt start	Ancillary
1	0.15	30	AUTO (5 kHz)	P A 55011aqp 55011aav	20 ms	9 kHz	10	OFF	OFF	...	L1, L2

Pulse Limiter ON
Ancillary = L2 7010
Limits:
55011aqp

Peak

Figure 33. Peak Test Result at 230-V AC

6.6 EMC

Texas Instruments tested this board for compliance using the following tests:

Table 11. EFC and Surge Tests

TEST	APPLICABLE STANDARD	TEST LEVEL	OBSERVATION
EFT Test	IEC 61000-4-4	a. Level 4 kV on Power Port b. Common mode and differential mode with all combinations c. Tested at 230 V AC	Result: Pass, Class A performance
Surge Test	IEC 61000-4-5	a. 2 kV Differential Mode b. 4 kV Common Mode c. Tested at 230 V AC	Result: Pass, Class A performance

6.7 Summary of Results

Table 12. Summary of Results

TEST	PARAMETER	TEST RESULT (OBSERVATION)
Line Regulation	20 to 250-V DC	< 1%
	80 to 276-V AC	< 1%
Efficiency	20 to 250-V DC	Up to 63 to 77% at full load
	80 to 276-V AC	Up to 70 to 78% at full load
Load Regulation	10 to 100% load variation	< 1%
	Cross Load Regulation for V01	±12 V < 1% 6.75 V < 4%
	Cross Load Regulation for V02	±12 V < 1% 6.75 V < 4%
Ripple		< 200 mV pk-pk for ±12 V
Ride through Performance	Dip in the output rails < 5% for time >75 ms after auxiliary input voltage falls to zero	> 100 ms

7 Bill of Materials

To download the complete bill of materials (BOM) for each board, see the design files at TIDA-00127.

Table 13. BOM

DESIGNATOR	QUANTITY	DESCRIPTION	PACKAGE REFERENCE	PART NUMBER	MANUFACTURER
!PCB1	1	Printed Circuit Board		TIDA-00127	Any
B1, B2, B3, B4, B5, B6	6	FERRITE CHIP 70 OHM 4000MA 0603		CIS10P700AC	Samsung
C1, C2, C5, C21	4	CAP FILM 0.47UF 560VDC RADIAL		R46KI347050P1M	Kemet
C3, C42	2	CAP CER 100PF 1KV 10% RADIAL		DEBB33A101KP2A	muRata
C4	1	CAP ALUM 33UF 450V 20% RADIAL		UCS2W330MHD6	Nichicon
C6	1	CAP ALUM 68UF 450V 20% RADIAL		EKXG451ELL680MMN3S	United Chemicon
C7, C8	2	CAP CER 330PF 300VAC 10% RADIAL		VY2331K29Y5SS63V7	Vishay
C9, C10, C19, C26	4	CAP CER 2200PF 300VAC 20% RADIAL		VY2222M35Y5US63V7	Vishay
C11, C20	2	CAP CER 10000PF 1KV 20% RADIAL		S103M47Z5UN63J7R	Vishay
C12	1	CAP ALUM 33UF 35V 20% RADIAL		35YXJ33M5X11	Rubycon
C13	1	CAP CER 470PF 50V 5% NP0 0603		06035A471JAT2A	AVX Corporation
C14	1	CAP, CERM, 22uF, 16V, +/-10%, X5R, 0805	0805	C2012X5R1C226K125AC	TDK
C16, C24, C29, C32	4	CAP CER 0.1UF 50V 10% X7R 0603		C0603C104K5RACTU	Kemet
C17	1	CAP, CERM, 2200pF, 50V, +/-10%, X7R, 0603		C0603C222K5RAC	Kemet
C18, C45	2	CAP CER 1UF 25V 10% X7R 0603		C0603C105K3RACTU	Kemet
C22	1	CAP CER 1000PF 500VAC 20% RADIAL		VY1102M35Y5UQ63V0	Vishay
C25, C31	2	CAP ALUM 220UF 35V 20% RADIAL		EEU-FM1V221L	Panasonic
C28	1	CAP, CERM, 4700pF, 2000V, +/-10%, X7R, 1812	1812	1812GC472KAT1A	AVX
C30	1	CAP ALUM 56UF 35V 20% RADIAL		UHE1V560MED	Nichicon
C33	1	CAP ALUM 33UF 35V 20% RADIAL		35YXJ33M5X11	Rubycon
C35, C36	2	CAP ALUM 470UF 35V 20% RADIAL		EEU-FM1V471	Panasonic
C37	1	CAP ALUM 220UF 25V 20% RADIAL		EKY-250ELL221MHB5D	United Chemicon
C39	1	CAP CER 0.33UF 25V 10% X7R 0603		C1608X7R1E334K080AC	TDK
C40	1	CAP CER 0.022UF 50V 10% X7R 0603		C0603C223K5RACTU	Kemet
C41	1	CAP CER 0.033UF 50V 10% X7R 0603		06035C333KAT2A	AVX Corporation
C43	1	CAP CER 330PF 50V 5% NP0 0603		06035A331JAT2A	AVX Corporation
C44	1	CAP CER 100PF 50V 10% NP0 0603		06035A101KAT2A	AVX Corporation
C46	1	CAP, CERM, 0.01uF, 1000V, +/-10%, X7R, 1210	1210	GRM32QR73A103KW01L	MuRata
C47	1	CAP, CERM, 0.068uF, 16V, +/-10%, X7R, 0603	0603	GRM188R71C683KA01D	MuRata

Table 13. BOM (continued)

DESIGNATOR	QUANTITY	DESCRIPTION	PACKAGE REFERENCE	PART NUMBER	MANUFACTURER
D1	1	Diode, Utrafast, Power Rectifier, 600V, 4A		MUR460RLG	OnSemi
D2, D3, D4, D5	4	Diode, Rectifier, 600V, 6A		6A6-T	Diodes
D6	1	Diode, Rectifier, 800V, 1A		1N4006-T	Diodes
D7	1	DIODE, Zener, 18V, .5W, 5%		1N5248B	Fairchild
D8	1	DIODE, Zener, 15V, .5W, 5%		1N5245BTR	Fairchild
D9	1	Diode, Schottky, 2-A, 80-V		CDBB280-G	MCC
D10	1	DIODE,Transient Voltage Suppressor,120V, 600W		P6KE120A	Littelfuse
D11, D14	2	Diode, Fast, 600V, 1A		1N4937	Fairchild
D12	1	Diode, Rectifier, Trr 20 ns, Vrrm 200V, 3A		ES3D-E3/57T	Fairchild
D13	1	Diode Schottky, 8A, 100V		SS8PH10-M3/86A	Vishay
D15	1	Diode, Signal, 200-mA, 100-V, 350-mW		1N4148TA	Fairchild
D16	1	Diode, Schottky, 40V, 1A, SOD-123	SOD-123	1N5819HW-7-F	Diodes Inc.
D17	1	Diode, Signal, 300-mA, 75-V, 350-mW	SOD-123	1N4148W-7-F	Diodes
F1	1	FUSE SLOW 250VAC 5A RADIAL		RST 5	BEL
FID1, FID2, FID3, FID4, FID5, FID6	6	Fiducial mark. There is nothing to buy or mount.	Fiducial	N/A	N/A
H1, H2, H3, H4	4	Mounting Hole M3 3.5mm	Screw	STD	STD
HT1, HT2	2	Heatsink, TO-220	1.181 x 2.402 inch	R2A-CT2-38E	Ohmite
J1, J2	2	Terminal Block, 2x1, 5.08mm, TH		OSTTC022162	On-Shore Technology
J3	1	Terminal Block, 3x1, 5.08 mm, TH		OSTTC032162	On-Shore Technology
L1	1	Inductor, 82uH		750342278	WE
L2	1	Inductor, Power Choke SS30V	1.220 x 0.886 inch	SS30V-R350047	Kemet
L3	1	CHOKE TOROID 1.0mH 10A VERT	0.728 x 1083 inch	744824101	WE
L5	1	INDUCTOR 2.2UH 4.1A RADIAL		LHL08TB2R2M	Taiyo Yuden
LBL1	1	Thermal Transfer Printable Labels, 0.650" W x 0.200" H - 10,000 per roll	PCB Label 0.650"H x 0.200"W	THT-14-423-10	Brady
Q1	1	MOSFET N-CH 600V 120MA SOT-223		BSP135 L6327	Infineon
Q2	1	MOSFET N-CH 600V 21MA SOT23		BSS126 H6327	Infineon
Q3	1	MOSFET, Nch, 600-V, 20A, 0.199 Ohms		AOTF20S60L	Alpha&Omega
Q4, Q5	2	MOSFET N-CH 60V 260MA SOT-23		2N7002ET1G	OnSemi
Q6	1	MOSFET, Nch, 600-V, 4A, 0.9 Ohms		AOTF4S60	Alpha&Omega
R1	1	RES 330 OHM 1W 5% 2512		RC6432J331CS	Samsung
R2	1	RES, 220 ohm, 1%, 0.1W, 0603	0603	RC0603FR-07220RL	Yageo America
R3, R30	2	RES 44.2K OHM 1/10W 1% 0603 SMD		RC0603FR-0744K2L	Yageo
R4	1	RES 1.33M OHM 1/10W 1% 0603 SMD		CRCW06031M33FKEA	Vishay Dale
R5, R7, R11	3	RES 649K OHM 1/4W 1% 1206 SMD		RC1206FR-07649KL	Yageo
R6, R25	2	RES 30.1K OHM 1/10W 1% 0603 SMD		RC0603FR-0730K1L	Yageo
R8	1	RES 1.00M OHM 1/10W 1% 0603 SMD		RC0603FR-071ML	Yageo
R9	1	RES 15.0 OHM 1/8W 1% 0805 SMD		RC0805FR-0715RL	Yageo
R10	1	RES, 402k ohm, 1%, 0.1W, 0603	0603	CRCW0603402KFKEA	Vishay-Dale
R12	1	RES, 1.00Meg ohm, 1%, 0.1W, 0603	0603	CRCW06031M00FKEA	Vishay-Dale
R13	1	RES 226 OHM 1/10W 1% 0603 SMD		RC0603FR-07226RL	Yageo
R14	1	RES 348K OHM 1/10W 1% 0603 SMD		RC0603FR-07348KL	Yageo
R15	1	RES 0.02 OHM 1W 1% 2512 SMD		LRMAM2512-R02FT4	TT/Welwyn
R16	1	RES, 127k ohm, 1%, 0.1W, 0603	0603	CRCW0603127KFKEA	Vishay-Dale
R17	1	RES 3.83K OHM 1/10W 1% 0603 SMD		RC0603FR-073K83L	Yageo
R20	1	RES 301K OHM 1/10W 1% 0603 SMD		RC0603FR-07301KL	Yageo
R21	1	RES 71.5K OHM 1/10W 1% 0603 SMD		RC0603FR-0771K5L	Yageo
R22	1	RES 1.21K OHM 1/10W 1% 0603 SMD		RC0603FR-071K21L	Yageo
R23	1	RES 8.20 OHM 1/4W 1% 1206 SMD		RC1206FR-078R2L	Yageo
R24	1	RES 10.5K OHM 1/10W 1% 0603 SMD		RC0603FR-0710K5L	Yageo
R26	1	RES 162K OHM 1/10W 1% 0603 SMD		RC0603FR-07162KL	Yageo
R28	1	RES 3.01K OHM 1/10W 1% 0603 SMD		RC0603FR-073K01L	Yageo
R29	1	RES 3.65K OHM 1/10W 1% 0603 SMD		RC0603FR-073K65L	Yageo
R31	1	RES 49.9 OHM 1/10W 1% 0603 SMD		RC0603FR-0749R9L	Yageo

Table 13. BOM (continued)

DESIGNATOR	QUANTITY	DESCRIPTION	PACKAGE REFERENCE	PART NUMBER	MANUFACTURER
R32	1	RES 162 OHM 1.5W 1% 2512 SMD	2512	CRCW2512162RFKEGHP	Vishay-Dale
R33	1	RES 1.00K OHM 1/10W 1% 0603 SMD		RC0603FR-071KL	Yageo
R34	1	RES 10.0 OHM 1/8W 1% 0805 SMD		RC0805FR-0710RL	Yageo
R35	1	RES 100K OHM 1/10W 1% 0603 SMD		RC0603FR-07100KL	Yageo
R36	1	RES 9.53K OHM 1/10W 1% 0603 SMD		RC0603FR-079K53L	Yageo
R37	1	RES 1.62K OHM 1/10W 1% 0603 SMD		RC0603FR-071K62L	Yageo
R38	1	RES 0.33 OHM 1W 1% 2010		CSRN2010FKR330	Stackpole
R39	1	RES 2.49K OHM 1/10W 1% 0603 SMD		RC0603FR-072K49L	Yageo
R40	1	RES 68 OHM 2W 1% 2512	2512	RHC2512FT68R0	Stackpole Electronics Inc
R41	1	RES, 27.0k ohm, 1%, 0.1W, 0603	0603	RC0603FR-0727KL	Yageo America
R42	1	RES, 4.30k ohm, 1%, 0.1W, 0603	0603	RC0603FR-074K3L	Yageo America
RT1, RT2, RT3	3	MOV, 300V		MOV-10D471KTR	Bourns
T1	1	Transformer, EI-30, Vertical		750342279	Wurth
U1	1	IC REG CTRLR BST FLYBK CM 10MSOP		TPS40210DGQ	TI
U2, U4	2	IC DETECTOR UNDER VOLT 3V SC70-5		LMS33460MG/NOPB	TI
U3	1	IC REG LDO NEG ADJ 1.5A TO252		LM337KVURG3	TI
U5	1	IC CTRLR PWM GREEN CM OVP 8SOIC		UCC28600DR	TI
U6	1	OPTOCOUPLER TRANS 5KVRMS 4DIP		LTV-817A	Lite-On
U7	1	IC VREF SHUNT PREC ADJ SOT23-3		TL431AIDBZT	TI
C15	0	CAP CER 470PF 50V 5% NP0 0603		06035A471JAT2A	AVX Corporation
C23, C27	0	CAP CER 330PF 250V 5% NP0 0603		C1608C0G2E331J080AA	TDK
C34	0	CAP CER 1000PF 250V 5% NP0 0603		C1608C0G2E102J080AA	TDK
C38	0	CAP CERAMIC, 25V, C0G, 10%		STD	STD
C48, C49	0	CAP, CERM, 0.068uF, 16V, +/-10%, X7R, 0603	0603	GRM188R71C683KA01D	MuRata
R18, R19	0	RES 33 OHM 1W 5% 2512		RC6432J330CS	Samsung
R27	0	RES 8.20 OHM 1W 5% 2512		6-1622820-6	TE Connectivity

8 Schematics

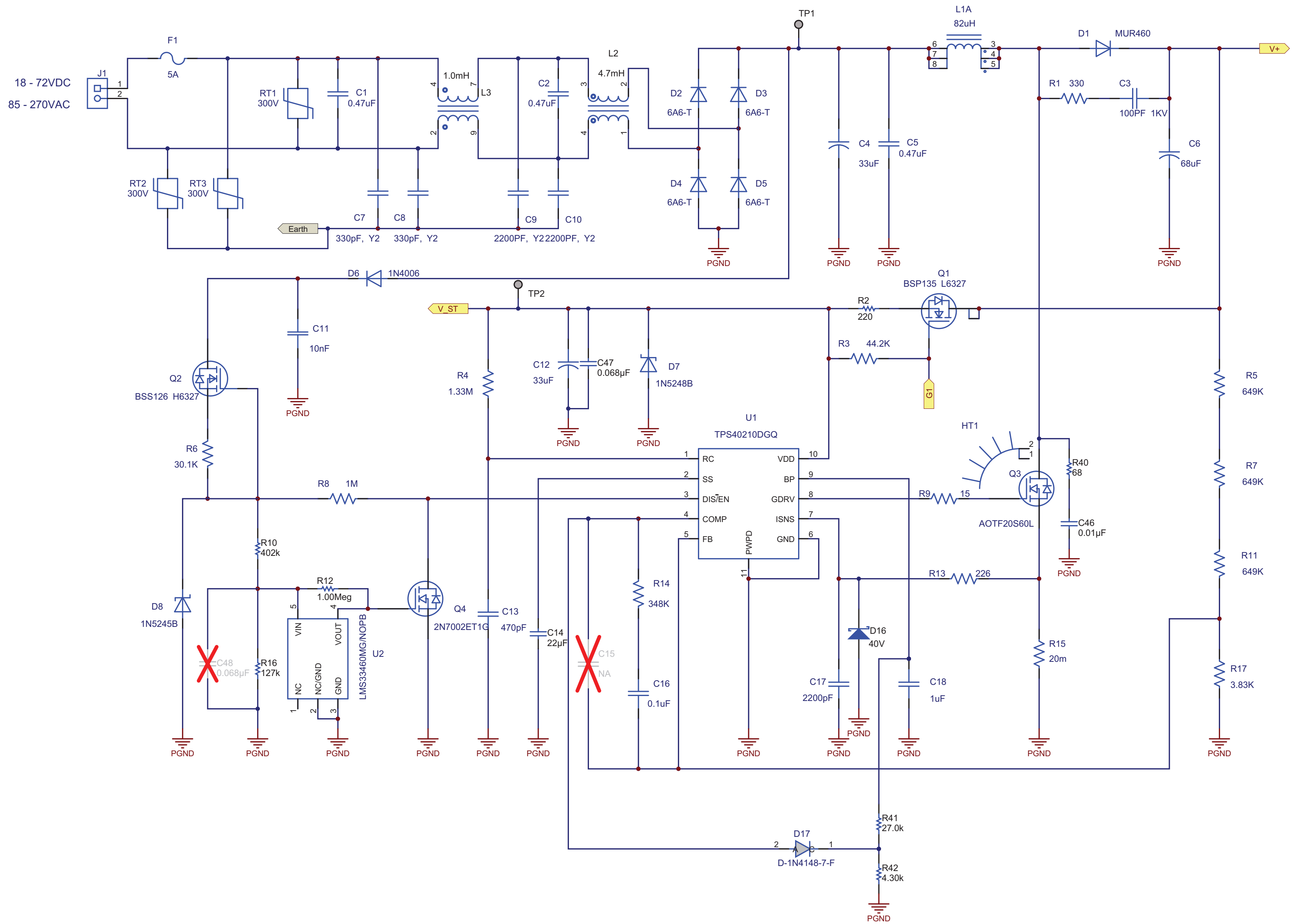


Figure 34. Schematic (Sheet 1 of 2)

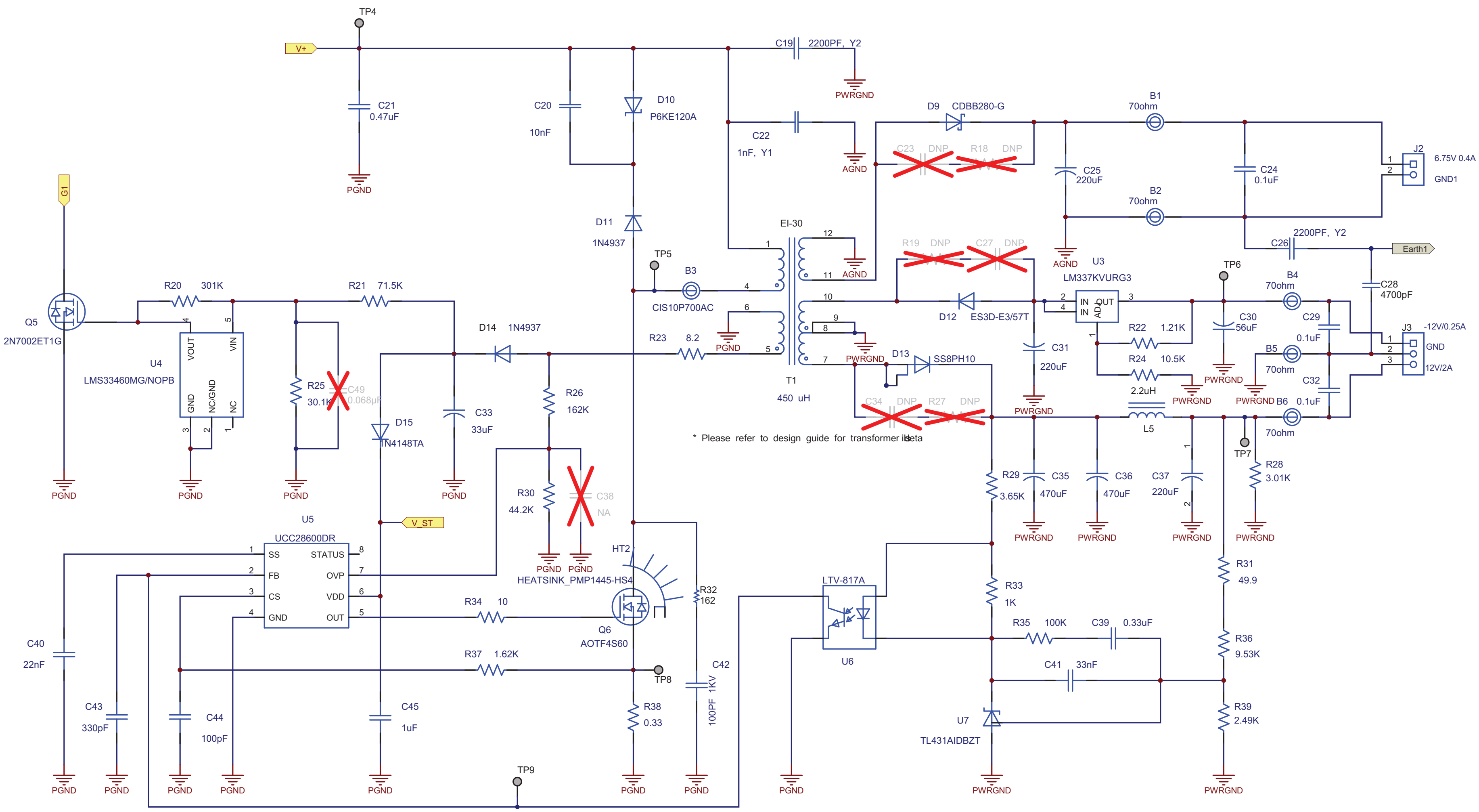


Figure 35. Schematic (Sheet 2 of 2)

9 Layer Plots

To download the layer plots for each board, see the design files at TIDA-00127. Figure 36 through Figure 44 show the layer plots.

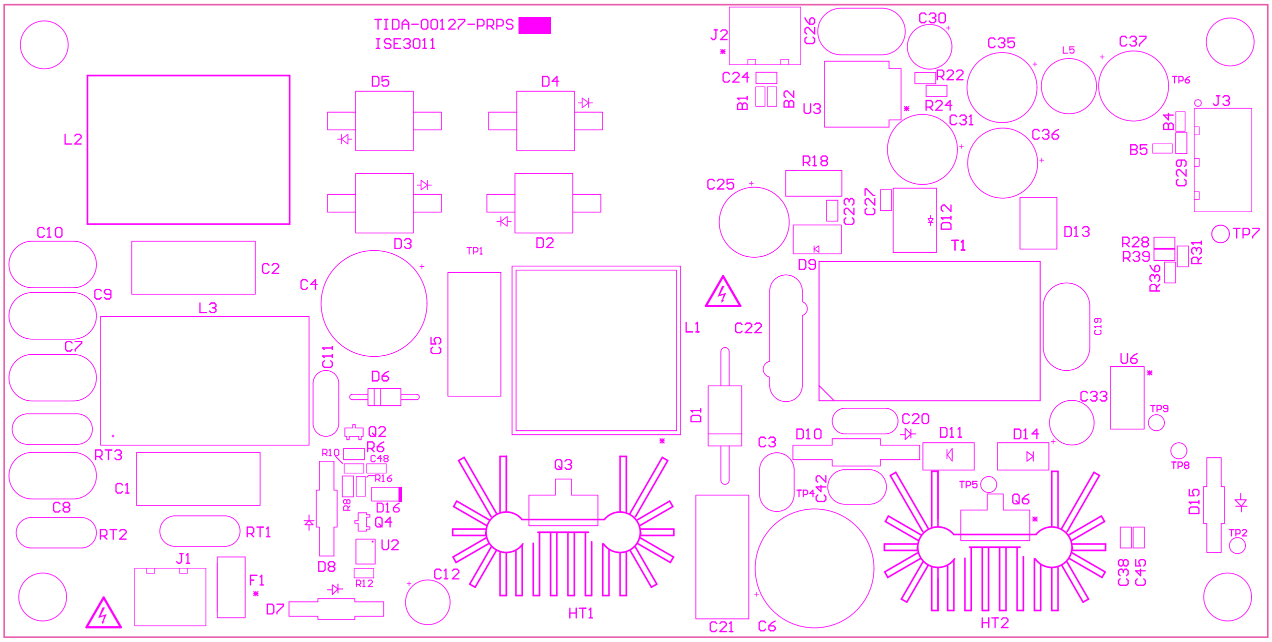


Figure 36. Top Overlay

Figure 37. Top Solder Mask

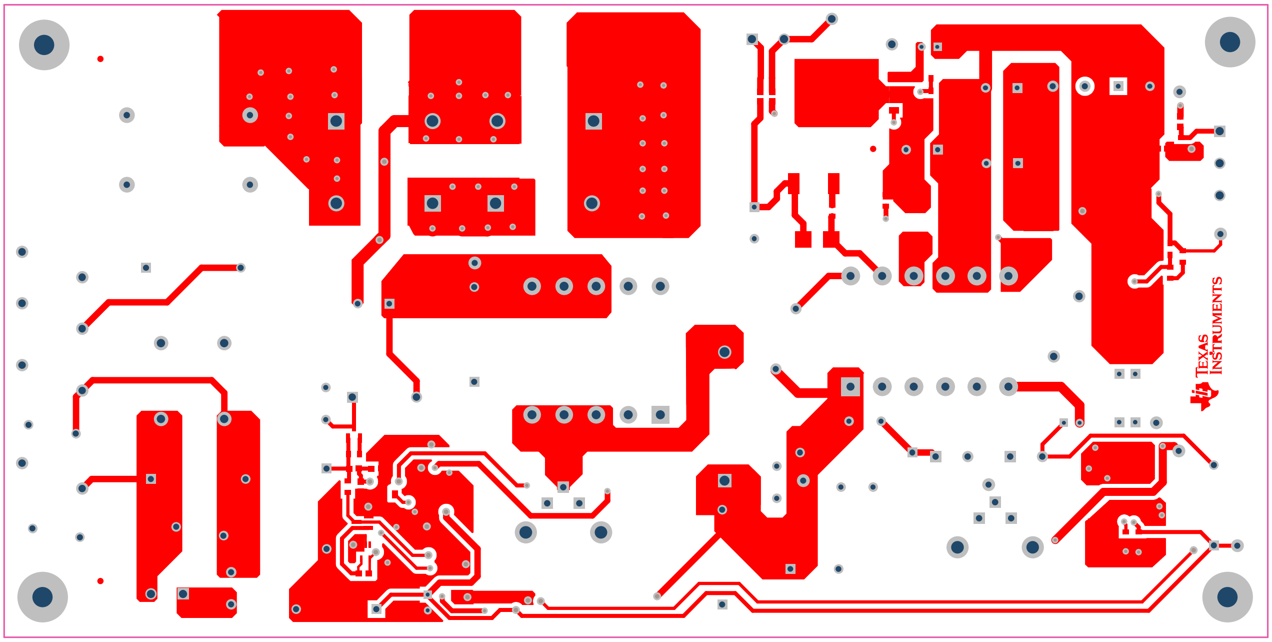


Figure 38. Top Layer

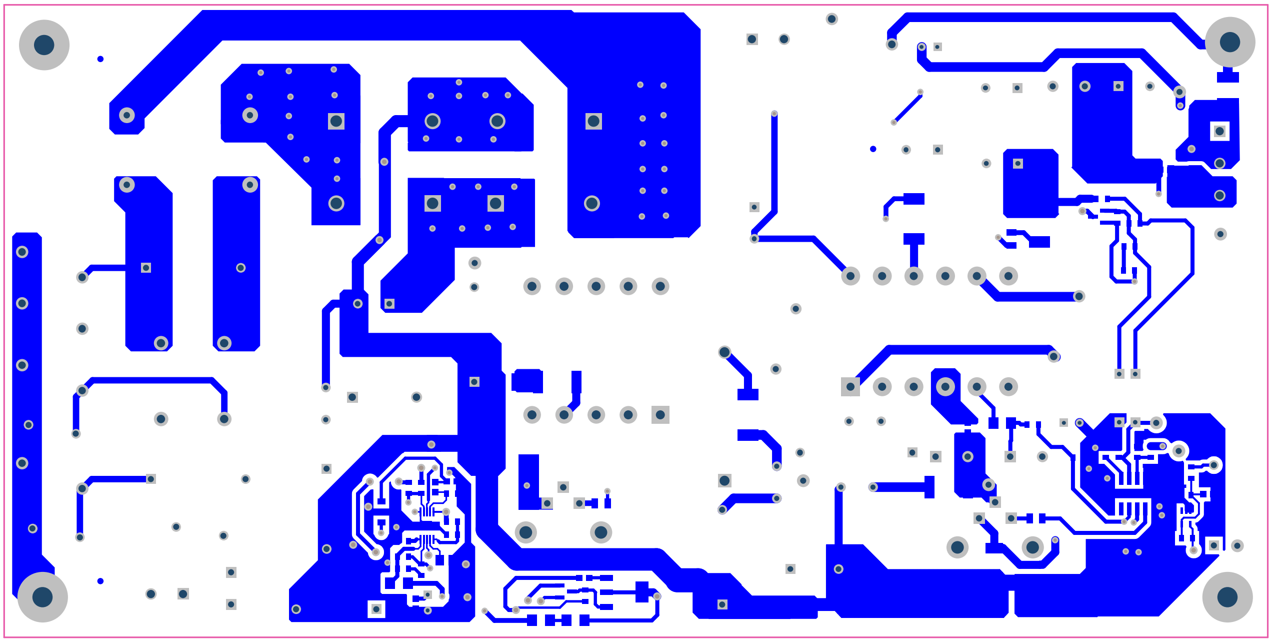


Figure 39. Bottom Layer

Figure 40. Bottom Solder Mask

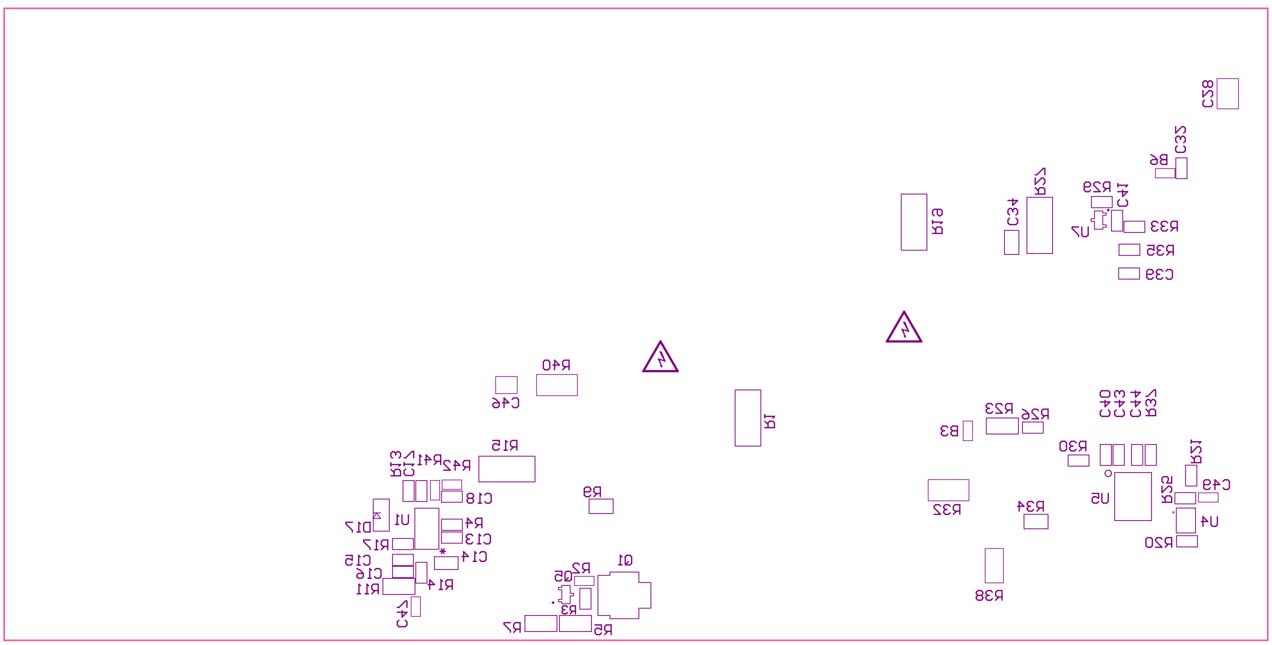


Figure 41. Bottom Overlay

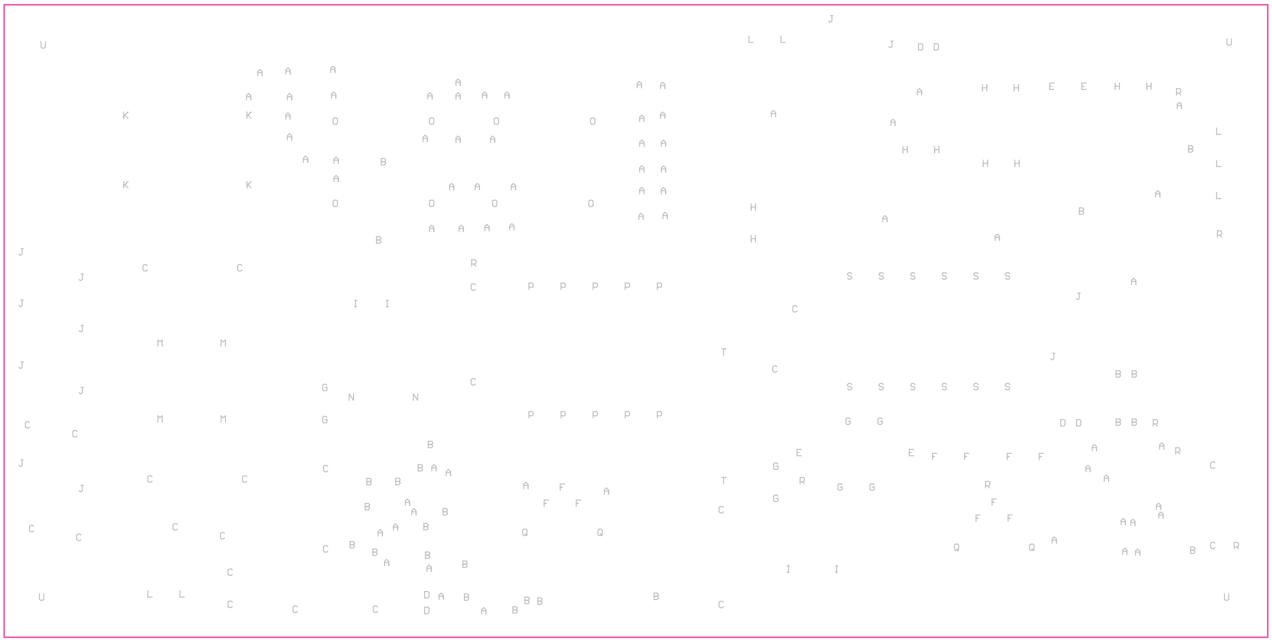


Figure 42. Drill Pattern

Symbol	Hit Count	Tool Size	Plated	Hole Type
A	69	20mil (0.508mm)	PTH	Round
D	6	25mil (0.635mm)	PTH	Round
B	25	28mil (0.711mm)	PTH	Round
H	10	31mil (0.787mm)	PTH	Round
G	8	32mil (0.813mm)	PTH	Round
I	4	35mil (0.889mm)	PTH	Round
E	4	37mil (0.94mm)	PTH	Round
R	8	37.992mil (0.965mm)	PTH	Round
C	24	38mil (0.965mm)	PTH	Round
K	4	39.37mil (1mm)	PTH	Round
F	10	40mil (1.016mm)	PTH	Round
N	2	45.276mil (1.15mm)	PTH	Round
J	12	47mil (1.194mm)	PTH	Round
S	12	50mil (1.27mm)	PTH	Round
L	7	51.181mil (1.3mm)	PTH	Round
M	4	52mil (1.321mm)	PTH	Round
P	10	55mil (1.397mm)	PTH	Round
T	2	62.992mil (1.6mm)	PTH	Round
O	8	71mil (1.803mm)	PTH	Round
Q	4	78.74mil (2mm)	PTH	Round
U	4	125.984mil (3.2mm)	PTH	Round
	237 Total			

Drill Table

Figure 43. Drill Pattern Table

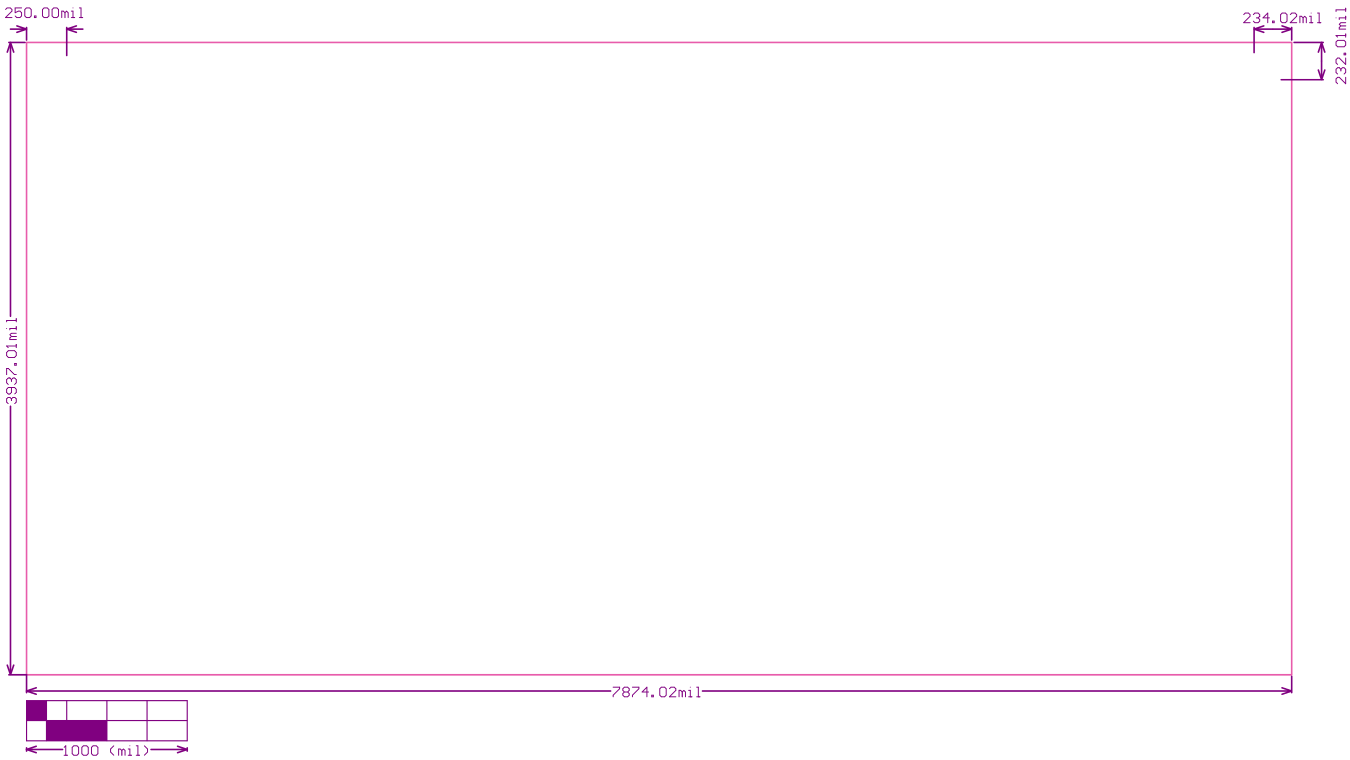


Figure 44. Board Dimensions

10 Altium Project

To download the Altium project files for each board, see the design files at TIDA-00127.

11 Gerber Files

To download the Gerber files for each board, see the design files at TIDA-00127.

12 Software Files

To download the software files for the reference design, see the design files at TIDA-00127.

13 About the Author

KALLIKUPPA MUNIYAPPA SREENIVASA is a systems architect at Texas Instruments where he is responsible for developing reference design solutions for the industrial segment. Sreenivasa brings to this role his experience in high-speed digital and analog systems design. Sreenivasa earned his bachelor of electronics (BE) in electronics and communication engineering (BE-E&C) from VTU, Mysore, India.

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