TI Designs
12-W Ultra-Wide Input Range Power Supply

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Design Resources

TIDA-00227	Tool Folder Containing Design Files
TPS40210DGQR	Product Folder
UCC28740	Product Folder
LMS33460MG/NOPB	Product Folder
TL431AIDBZ	Product Folder

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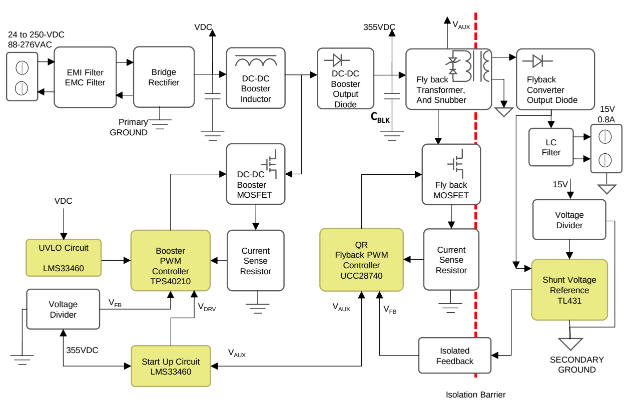
Design Features

The 12-W Ultra-Wide Input Range Power Supply is a reference design that is primarily targeted for protection relays. This design is a single-board solution that handles an ultra-wide range of AC or DC inputs.

- Supply Voltage Range
  - 24-V to 250-V DC or 88-V to 276-V AC
- Output Voltage at Nominal Supply Voltage
  - 15 V, 0.8 A
  - Total Output Power 12 W
  - Line Regulation < ±3%
    - 21-V to 250-V DC and 80-V to 276-V AC
  - Load Regulation < ±3%
    - (10 to 100%)
  - Form Factor
    - PCB Dimension 100 × 100 mm
- Meets Pre-Compliance Test Requirements
  - IEC61000-4 for EFT and Surge
  - EN55011 Class A Conducted Emission
  - IEC61000-4-11 (AC) and IEC61000-4-29 (DC) for Voltage Dips and Interruptions with Reduced Bulk Capacitor

Featured Applications

- Protection Relay: Single Function and Multifunction
- Substation IED and Automation Products
- Power Managers



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1 System Description

Protection relays play a critical role in electrical grids, substations, and power distribution systems. These relays protect the electrical power system against different electrical faults. The heart of this protection relay design is a smart controlling unit that continuously monitors electrical parameters such as voltages, currents, and frequencies. This smart controlling unit also issues trip commands to appropriate circuit breakers during faults.

There are different types of relays, depending upon the stage used. Types of protection relays include: generator protection, distance protection, overvoltage protection, overcurrent protection, and differential protection.

Protection relays are either self-powered or powered by auxiliary ports.

1.1 Power Supply Input Voltage

The input power supply can vary from 20-V DC to 250-V DC and 40-V AC to 250-V AC. The complete range of the operating input power supply voltage range is divided into multiple types.

- Type 1: 20- to 65-V DC
- Type 2: 37- to 150-V DC, 32 to 110 V AC
- Type 3: 87- to 300-V DC, 80 to 265-V AC

NOTE: Categorization of input into number of types of input range is dependent on manufacturers.

The burden on the auxiliary supply depends on the features offered by the protection relay and can vary from 4 W to 12 W for many of the protection relays. Protection relays with enhanced communication and I/O features may consume > 12 W.

1.2 Power Supply Interruption (Critical Protection-Relay Requirement)

One of the critical requirement when dealing with protection relays is to withstand the interruption of input voltage without restarting. The power supply interruption time depends on the power consumption of the relay and reduces with an increase in consumption.

To achieve the required backup time, larger capacitors are used. Electrolytic capacitors have reliability concerns; therefore, higher values may not be preferred.

This TI design reduces the capacitance required for the power supply to comply IEC61000-4-11 (AC) and IEC61000-4-29 (DC) for voltage variations and interruption.

1.3 12-W Power Supply

This design guide provides details to design a 12-W power supply used in protection relay. This 12-W ultra-wide range input-supply design serves as a ready-to-use reference design for protection relay. This design is a single-board power solution that handles an ultra-wide input range of AC or DC inputs. TI has a large portfolio of power solutions that can be used to design this power supply.

See Section 7 for the required schematics, PCB, test reports, and design calculations to design the power supply with reduced effort.

2 Design Features

Typical power supply requirements are shown in Table 1.

Table 1. Power Supply Requirements

REQUIREMENTS	REQUIREMENT PARAMETER	PARAMETER VALUES
Functional requirement	Output power in W	12
	Input voltage DC	24-V to 250-V DC
	Input voltage AC	88-V to 276-V AC
	Output voltages and current	15 V, 0.8 A
	Load regulation — 10 to 100%	<±3%
	Line regulation — AC/DC inputs	<±3%
	Output ripple	<200-mV peak-to-peak at 15 V
Pre-compliance	Conducted Emission	EN55011 Class A
	EFT	IEC 61000-4-4, Level 4
	Surge	IEC 61000-4-5, Level 3 - Differential Mode Level 4 - Common Mode
Permissible power interruption to maintain normal operation	<100 ms at 24-V DC	The design should support 15 V at 0.8 A during the interruption time specified with 100% load.

3 Block Diagram

The 12-W power-supply design handles ultra-wide ranges of AC or DC inputs, making the power-supply a suitable platform for a variety of protection relays. The power supply provides excellent line and load regulation. The design has been pre-compliance tested for IEC61000-4 (EFT and Surge) and EN55011 Class A (Interference).

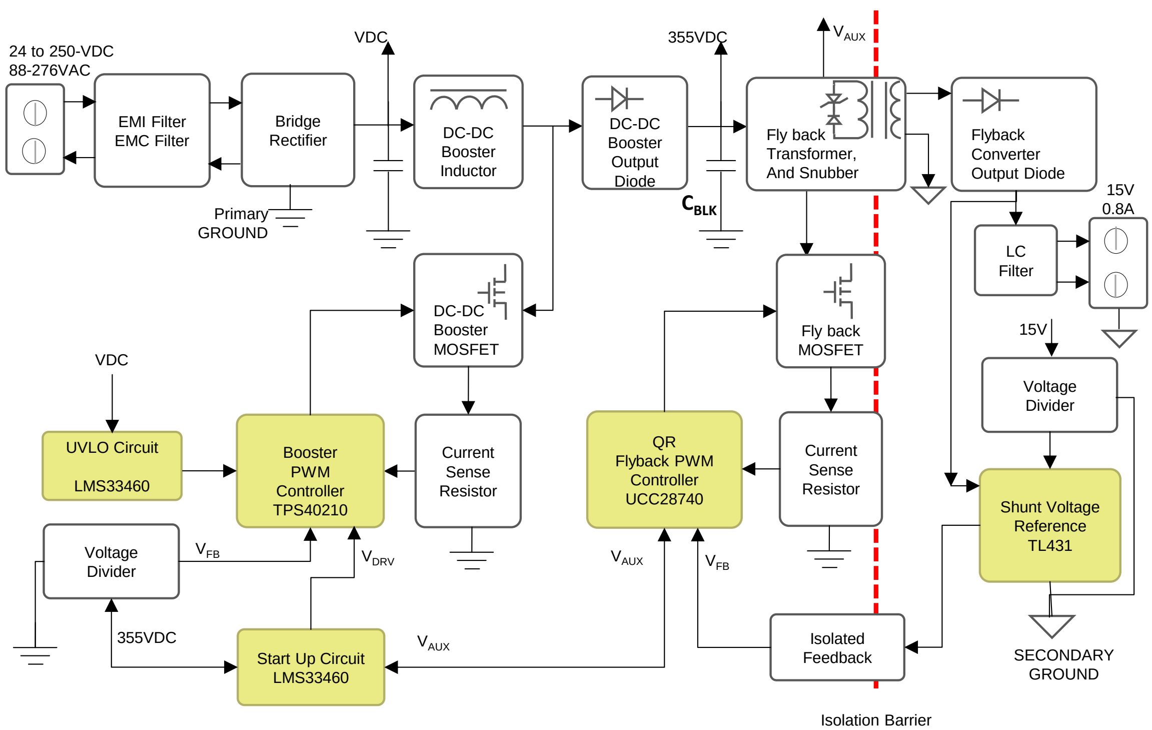


Figure 1. Block Diagram

This design uses a two-stage conversion topology. This design includes a DC-DC boost converter which boosts input voltage (24-V to 250-V DC input or rectified 88-V to 276-V AC input) to the 355-V DC output. This boost DC voltage is the input to a quasi-resonant flyback converter. The output of the flyback converter is 15 V, 0.8 A.

The design has the following functional blocks:

3.1 Power Supply Inputs and Filter

The board has a single input connector for DC or AC voltages.

The input filter has the following components:

1. Common Mode Filter (Common Mode Choke and Y caps) and Differential Mode Filter (X caps).
2. MOV for common and differential mode surge protection.

3.2 Input Rectifier

Due to the ultra-wide range of DC input voltage, the current drawn by the power supply at 20-V DC will be ~ 2 A. To take care of inrush and thermal requirements, an 8-A bridge rectifier is selected. The bridge rectifier has a PIV of 600 V.

3.3 DC Voltage Booster

The DC output of bridge rectifier is applied to the DC-DC Booster designed using a TPS40210 current-mode controller. This booster works in discontinuous conduction mode and the output of the booster is set to around 355-V DC (for a 24-V to 250-V DC or 88-V to 276-V AC input). Discontinuous mode has lower loss compared to CCM mode.

3.4 Flyback Converter

The second stage uses a flyback converter using a Texas Instruments' device, UCC28740, green-mode controller. The output of the DC voltage booster is applied to the flyback converter. Output of the flyback converter is 15 V, 0.8 A.

The flyback converter has operating input range of 110-V DC to 355-V DC, regardless of auxiliary voltage input. This operating input range results in a lower bulk-capacitor value requirement to meet the voltage interruption test requirements, as specified in IEC61000-4-11 (AC) and IEC61000-4-29 (DC).

3.5 Snubbers

The design uses snubber circuits across DC-DC booster MOSFET, flyback converter MOSFET, and output diodes. These circuits also help reduce EMI.

4 Circuit Design and Component Selection

For more information on each of these devices, refer to the respective product folders at www.TI.com.

4.1 Front-End EMC Filter

For calculation of the EMC filter and other EMC considerations, see the following application notes available on 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* (SNVA489).
- *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 V 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

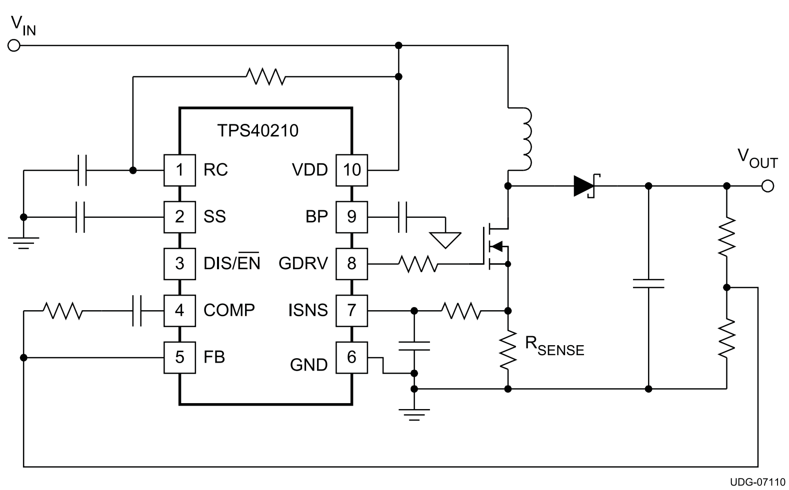


Figure 2. DC-DC Booster Design Using theTPS40210DGQ

4.2.1 Power Supply Design Parameters

1. Input voltage DC: 24-V to 250-V DC
2. Input voltage AC: 88-V to 276-V AC
3. Output voltage: 15 V, 0.8 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, *Inductor and Flyback Transformer Design* (SLUP127).

4.2.2.1 Booster Design Parameters

- Minimum DC input voltage, (V):
  $V_{INDC(MIN)}$ = 18 V
- Maximum DC input voltage, (V):
  $V_{INDCMAX}$ = 250 V
- Minimum AC input voltage, (V):
  $V_{INAC(MIN)}$ = 80 V
- Maximum AC input voltage, (V):
  $V_{INAC(MAX)}$ = 276 V
- Bridge rectifier drop, (V):
  V_{BR} = 0.7 V
- Bus voltage, (V):

$$V_{BUS(MAX)} = V_{INAC(MAX)} \times 1.4142 - 2 \times V_{BR} \quad (1)$$

$$V_{BUS(MIN)} = V_{INDC(MIN)} - 2 \times V_{BR} \quad (2)$$

$$V_{BUS(MAX)} = 389\text{-V DC} \quad (3)$$

  The range of V_{BUS} can be from 16.6-V DC to 389-V DC
- Second stage output power:
  $P_{FLYBACKOUT}$ = 12.5 W
  - Flyback output $V_{FLYBACKOUT}$ = 15 V
  - Flyback output diode drop = 0.7 V
  - Flyback output current 0.8 A

$$P_{FLYBACKOUT} = (V_{FLYBACKOUT} + V_D) \times I_{FLYBACKOUT} = (15 + 0.7) \times 0.8 \sim 12.5\text{ W} \quad (4)$$

- Efficiency of second stage:
  τ2 = (80%) 0.8
- Output power of booster:
  $P_{BOOSTERIN}$ = 16 W
- Efficiency of booster:
  τ1 = (80%) 0.8
- Input power of booster:
  $P_{BOOSTERIN}$ = 20 W
- Output voltage of the booster:
  $V_{BOOSTOUT}$ = 355 V

  Booster output is set at 355 V for 18- to 250-V DC or 88- to 250-V AC. Above 250-V AC, the boost function is disabled, and rectified voltage appears directly across the booster-output capacitor. The booster output is set to 355 V to take care of maximum duty-cycle limitation of TPS40210. At 276-V AC, the booster output will be around 390-V DC. For the calculation of booster parameters, 355-V DC is considered as booster output.

- Output average current of the booster:

$$I_{BOOSTOUT} = \frac{P_{BOOSTEROUT}}{V_{BOOSTOUT}} = \frac{20}{355} = 0.044\ A \quad (5)$$

- Output load of the booster:

$$R_{BOOSTOUT} = \frac{V_{BOOSTOUT}}{I_{BOOSTOUT}} = 8066\ \Omega \quad (6)$$

4.2.2.2 Preliminary Calculation

- Voltage gain of the booster:

$$M_{MAX} = \frac{V_{BOOSTOUT}}{V_{BUSMIN}} = \frac{355}{16.6} = 21.39 \quad (7)$$

$$M_{MIN} = \frac{V_{BOOSTOUT}}{V_{BUSMAX}} = \frac{355}{389} = 0.91 \quad (8)$$

- Duty cycle:

$$D_{MAX} = 1 - \frac{1}{M_{MAX}} = 0.95 \quad (9)$$

- Switching frequency, (Hz):
  F_{SW} = 35000
- Time period, s:
  T_{SW} = 28.57 µs
- Critical inductor value to keep in discontinuous mode:

$$L_{CRITICAL} \leq 0.5 \times R_{BOOSTOUT} \times T_{SW} \times D_{MAX} \times (1 - D_{MAX}) \times (1 - D_{MAX}) \leq 240\ \mu H \quad (10)$$

- Choose value of booster inductor:
  $L_{BOOSTER}$ = 150 µH to avoid transition from DCM to CCM mode at lower voltage input range.

  Justification for using 150 µH inductor value is explained in the following paragraphs.

  As per the application information given in *TPS40210, TPS40211 4.5-V to 52-V Input Current Mode Boost Controller* (SLUS772).

  Converters using freewheeling diodes have a load-current level at which they transition from discontinuous conduction to continuous conduction. This is the point where the inductor current just falls to zero. At higher load currents, the inductor current does not fall to zero but remains flowing in a positive direction and assumes a trapezoidal wave shape as opposed to a triangular wave shape. This load boundary between discontinuous conduction and continuous conduction can be found for a set of converter parameters as in Equation 11.

$$I_{OUT(CRIT)} = \frac{(V_{OUT} + V_D - V_{IN}) \times (V_{IN})^2}{2 \times (V_{OUT} + V_D)^2 \times f_{SW} \times L}$$

  where

  -
  - V_{OUT} is the output voltage of the converter in V
  - V_D is the forward conduction voltage drop across the rectifier or catch diode in V
  - V_{IN} is the input voltage to the converter in V
  - I_{OUT} is the output current of the converter in A
  - L is the inductor value in H
  - f_{SW} is the switching frequency in Hz (11)

  Based on Equation 11, the results in Table 2 and Table 3 are obtained for different values of input voltages for two different values of booster inductor.

Table 2. DCM to CCM Transition for 250 µH Inductor

L, H	V_O, V	V_D, V	Board V_{IN}, V	V_{IN}, V After Bridge Rectifier	f_{SW}, Hz	DCM/CCM Boundary Mode Current
0.00025	355	0.7	29.5	28	35000	0.116
0.00025	355	0.7	28.5	27	35000	0.108
0.00025	355	0.7	27.5	26	35000	0.101
0.00025	355	0.7	26.5	25	35000	0.093
0.00025	355	0.7	25.5	24	35000	0.086
0.00025	355	0.7	24.5	23	35000	0.079
0.00025	355	0.7	23.5	22	35000	0.073
0.00025	355	0.7	22.5	21	35000	0.067
0.00025	355	0.7	21.5	20	35000	0.061
0.00025	355	0.7	20.5	19	35000	0.055
0.00025	355	0.7	19.5	18	35000	0.049
0.00025	355	0.7	18.5	17	35000	0.044
0.00025	355	0.7	17.5	16	35000	0.039

Table 2 indicates that at lower input voltage of 19.5 V, the booster crosses from DCM to CCM mode at a load current of 0.049 A; thus, resulting in a state of instability.

With 150-µH Inductor, DCM to CCM mode current is always more than the booster output current I_o = 0.045 A required at 18-V DC, so no state of instability is reached as shown in Table 3.

Table 3. DCM to CCM Transition for 150 µH Inductor

L, H	V_O, V	V_D, V	Board V_{IN}, V	V_{IN}, V After Bridge Rectifier	f_{SW}, Hz	DCM/CCM Boundary Mode Current
0.00015	355	0.7	29.5	28	35000	0.193
0.00015	355	0.7	28.5	27	35000	0.18
0.00015	355	0.7	27.5	26	35000	0.168
0.00015	355	0.7	26.5	25	35000	0.156
0.00015	355	0.7	25.5	24	35000	0.144
0.00015	355	0.7	24.5	23	35000	0.132
0.00015	355	0.7	23.5	22	35000	0.122
0.00015	355	0.7	22.5	21	35000	0.111
0.00015	355	0.7	21.5	20	35000	0.101
0.00015	355	0.7	20.5	19	35000	0.091
0.00015	355	0.7	19.5	18	35000	0.082
0.00015	355	0.7	18.5	17	35000	0.074
0.00015	355	0.7	17.5	16	35000	0.065

- Inductor peak current, (A):

$$I_{LPEAK} = \frac{V_{BUSMIN}}{L_{BOOSTER}} \times T_{SW} \times D_{MAX} = 3.01\,A \quad (12)$$

- Inductor minimum current, (A):
  I_{MIN} = 0 A
- Average value of trapezoidal waveform, (A):

$$I_{PA} = 0.5 \times (I_{LPEAK} + I_{MIN}) = 1.51\ A \quad (13)$$

- DC value of trapezoidal waveform, (A):

$$I_{DC} = D_{MAX} \times I_{PA} = 1.44\ A \quad (14)$$

- RMS value of trapezoidal waveform, (A):

$$I_{RMS} = \sqrt{[D_{MAX} \times \{(I_{LPEAK} \times I_{MIN}) + (I_{LPEAK} - I_{MIN}) \times (I_{LPEAK} - I_{MIN})\}]} = 1.69\ A \quad (15)$$

- AC value of trapezoidal waveform, (A):

$$I_{AC} = \sqrt{I_{RMS}^2 - I_{DC}^2} = 0.89\ A \quad (16)$$

- Maximum-peak short-circuit current:

$$I_{SCPK} = I_{LPEAK} \times 1.2 = 3.62\ A \quad (17)$$

An inductor of 150 µH with rated current shown in Equation 17 is required.

4.2.2.3 *Switching Frequency*

Switching frequency of the DC-DC converter is chosen to be 35 KHz so as to get enough ON time at higher line voltages. RT and CT values are chosen to be 1.33 M and 470 pF.

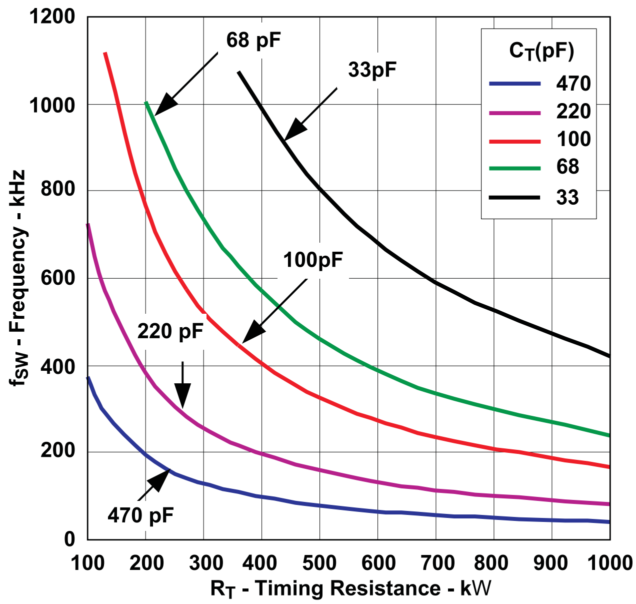


Figure 3. Frequency versus Timing Resistance for TPS40210

4.2.2.4 Output Diode Selection

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

$$V_{PIVBDIODE} \geq 1.25 \times V_{BOOSTOUT} \geq 450\ V \quad (18)$$

- The diode must have a reverse breakdown voltage greater than 500 V. The rectifier diode peak and average currents are estimated by:
  $I_{BD(AVG)} = I_{BOOSTOUT} = 0.045\ A$
  $I_{BD(PEAK)} = I_{LPEAK} = 3.01\ A$
- The power dissipation in the diode is estimated by:

$$P_{BDiode} = I_{BD(AVG)} \times V_F = 0.03\ W \quad (19)$$

Table 4. Diode Specifications

SELECTED DIODE	
Part Number	STTH8L06
Type of Diode	Ultrafast
PIV	600 V
IF	8 A
Surge Non-repetitive Forward Current	120 A

4.2.2.5 Output Capacitor Selection

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

where

- $V_{BOOSTOUTRIPPLE} = 0.5\ V$
- C_{OUT} with 20% tolerance = 23 µF (20)

$$ESR\,C_{OUT} = \frac{(7 \times V_{BOOSTOUTRIPPLE})}{(8 \times (I_{LPEAK} - I_{BOOSTOUT}))} = 0.083\ \Omega \quad (21)$$

Table 5. Output Capacitor Selection

Selected C_{OUT}	33	µF	450	V

4.2.2.6 Current Sense and Current Limit

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

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

where

- $V_{ISNS(OC)}$ = 0.15 V
- R_{ISNS} is approximately 20 mΩ (22)

- Power Dissipation in the current sense resistor:

$P_{ISNS} = I^2_{RMS} \times R_{ISNS} \times D_{MAX}$ ~ 1 W (23)

4.2.2.7 Soft Start Capacitor

The capacitor on the SS pin 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 pin, the peak voltage must be kept below the overcurrent threshold voltage. The voltage on the ISNS pin 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:

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

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

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 pin, in F
- V_{BP} is the value of the voltage on BP pin, in V
- $V_{SS(ofst)}$ is the approximate level shift from the SS pin to the error amplifier (approximately 700 mV)
- V_{FB} is the error amplifier reference voltage, 700 mV typical
- Considering I_{EXT} = 0.044 A and $I_{OUT(OC)}$ = 0.053 A, t_{SS} is 1.33 seconds and C_{SS} = 22 µF (24)

4.2.2.8 Duty Cycle Clamp

The TPS40210 has a minimum off time of approximately 200 ns and a minimum on time of 300 ns. These two constraints place limitations on the operating frequency that can be used for a given input-to-output conversion ratio. To keep these limits in check, a duty cycle clamp is used at an input voltage value less than 24 V. This is achieved by clamping the compensation pin voltage of TPS40210. The value is clamped to a voltage that is the sum of voltages obtained at R13 and R15 across pin 9 of TPS40210 and the voltage drop across the Diode (D3) that is connected between the resistive divider and the compensation pin.

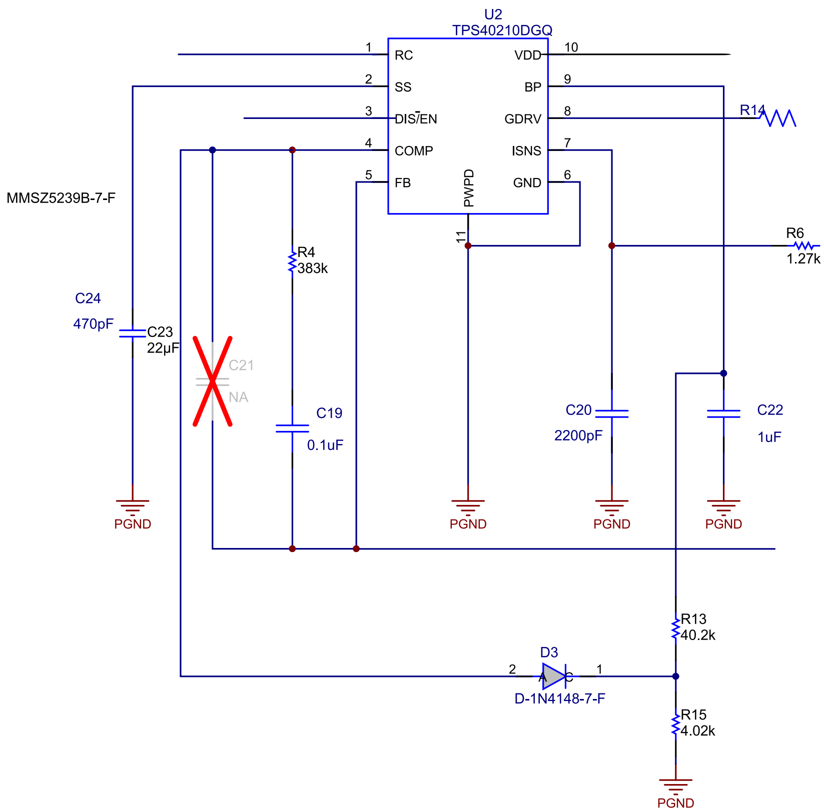


Figure 4. Duty Cycle Limiting Circuit

4.3 Flyback Converter Design Using UCC28740

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

- Working input voltage range: 110-V to 390-V DC
- Output voltage and power:
  - 15 V, 0.8 A
  - Total power 12 W

The design uses a quasi-resonant mode topology. Quasi-resonant topology has reduced EMI, lower switching losses for higher power outputs, compared to a conventional hard-switched converter with fixed switching frequency.

The UCC28740 isolated-flyback power-supply controller provides constant voltage (CV) using an opto-coupler to improve transient response for large-load variations. Constant-current (CC) regulation is accomplished through primary-side regulation (PSR) techniques. This device processes information from opto-coupled feedback and an auxiliary flyback winding for precise high-performance control of output voltage and current.

An internal 700-V startup switch, dynamically-controlled operating states, and a tailored modulation profile support ultra-low standby power without sacrificing startup time or output transient response.

Control algorithms in the UCC28740 allow operating efficiencies to meet or exceed applicable standards. The drive output interfaces to a MOSFET power switch. Discontinuous conduction mode (DCM) with valley switching reduces switching losses. Modulation of switching frequency and primary current peak amplitude (FM and AM) keeps the conversion efficiency high across the entire load and line ranges.

The controller has a maximum switching frequency of 100 kHz and always maintains control of the peak-primary current in the transformer. Protection features keep primary and secondary component stresses in check. A minimum switching frequency of 170 Hz facilitates the achievement of less than 10-mW no-load power.

UCC28740 Features

- Less than 10-mW no-load power capability
- Opto-coupled feedback for CV, and primary-side Regulation (PSR) for CC
- Enables ±1% voltage regulation and ±5% current
- Regulation across line and load
- 700-V Startup switch
- 100-kHz Maximum switching frequency enables
- High-power-density charger designs
- Resonant-ring valley-switching operation for highest overall efficiency
- Frequency dithering to ease EMI compliance
- Clamped gate-drive output for MOSFET
- Overvoltage, low-line, and overcurrent protection functions
- SOIC-7 package

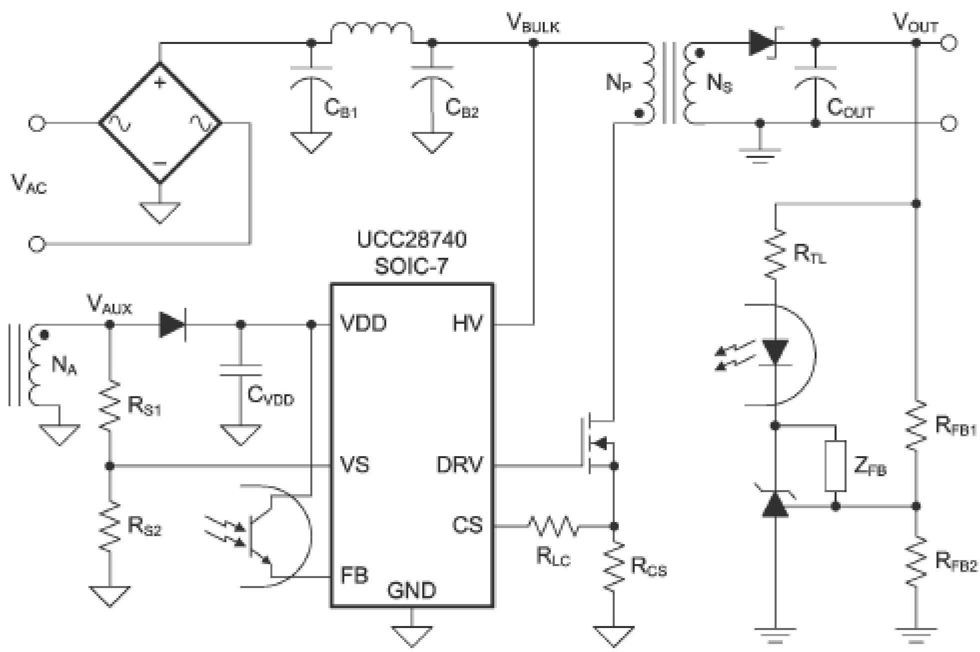


Figure 5. Typical Application Using UCC28710

4.3.1 Magnetics Calculation for Booster Inductor

The following calculations are based on *Exposing the Inner Behavior of a Quasi-Resonant Flyback Converter* (SLUP302).

4.3.2 Flyback Design Parameters

- DC input voltage, V $V_{INDCMIN}$: 110
- DC input voltage, V $V_{INDCMAX}$: 390
- Output voltage-01, V V_{01} = 15.0
- Output current, A I_{01}: 0.8
- Output diode voltage drop, V_D = 0.7
- Total output load, $P_{SLOAD} = (V_{01} + V_D) \times I_{01}$ = 12.5 W
- Efficiency of flyback converter, τ = 0.8
- Primary input power = 15.6 W
- Turn ratio calculation

$$N_{PS} = \frac{V_{INDCMAX}}{(V_{DBLOCKING} - (V_{01} + V_D))}$$

$$N_{PS} = \frac{V_{INDCMAX}}{V_{DBLOCKING} - (V_{01} + V_D)} = 6 \qquad (25)$$

- Considering the blocking voltage of the output diode, $V_{DBLOCKING}$ = 60 V

4.3.3 Primary Inductance Calculation

Figure 6 represents the volt-second product during the on-time and the volt-second product during the demagnetizing time. During every switching cycle, the flyback transformer maintains energy balance. Equating the on-time energy with the demagnetizing energy (with respect to the primary side) and then substituting for t_{DEMAG} allows the calculation of t_{ON}.

$$V_{INDCMIN} \times t_{ON} = N_{PS} \times (V_{01} + V_D) \times t_{DEMAG}$$

$$t_{DEMAG} = T_{SW} - t_{ON} - t_{RES}$$

$$t_{ON} = \frac{N_{PS} \times (V_{O1} + V_D) \times (T_{SW} - t_{RES})}{(V_{DCINMIN} + N_{PS} \times (V_{O1} + V_D))} \quad (26)$$

The resonance created by the primary inductance and parasitic capacitance must last for a long-enough time so that the waveform can ring down to a level that the controller can interpret as indication that another switching cycle can begin. This time, t_{RES} is equal to at least one-half of the resonant period, which is the time to transition from peak to valley. The switching period is equal to the inverse of f_{SW} and must consist of the on-time, t_{ON}, the demagnetizing time, t_{DEMAG} and t_{RES}.

$$T_{SW} = t_{ON} + t_{DEMAG} + t_{RES} \quad (27)$$

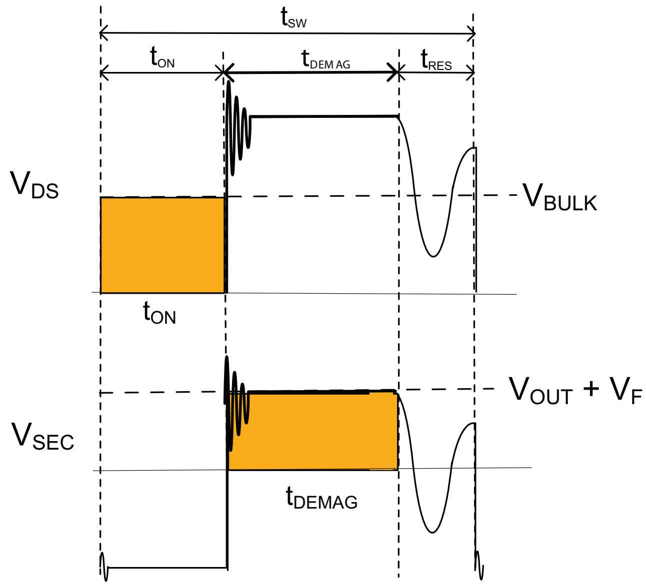


Figure 6. Volt Seconds During the On-Time Must Equal the Volt Seconds During the Demagnetizing Time for Energy Balance

Assuming f_{RES} will be less than 500 KHz so an initial assumption of t_{RES} = 1 µs is a valid starting point.

t_{RES} = 1 µS

By putting the values into Equation 27 we get t_{ON}.

t_{ON} = 6.5 µS

After calculating the initial on-time it is necessary to calculate the primary inductance, $L_{PRIMARY}$ which will satisfy the energy requirement of the load at the switching frequency set for the minimum input voltage.

$$L_{PRIMARY} = \tau \times (V_{INDCMIN} \times t_{ON})^2 \times f_{SW} / (2 \times P_{OUT}) = 1094\ \mu H \quad (28)$$

By putting the respective parameter values in Equation 28 for $L_{PRIMARY}$, we get:

$L_{PRIMARY}$ = 1094 µH

$$I_{PRIPEAK} = \sqrt{\left(\frac{2 \times P_{OUT}}{\tau \times L_{PRIMARY} \times f_{SW}}\right)} = 0.63\,A \quad (29)$$

Initial calculations result in a primary inductance $L_{PRIMARY}$ = 1094 µH and a peak primary current of 0.63 A.

If initial calculations for t_{ON} and $I_{PRIPEAK}$ fall outside the dynamic modulations range of the controller the value for $L_{PRIMARY}$ must be iterated so that regulation is achieved over the frequency range enveloped by the minimum and maximum frequency clamps — all while satisfying the maximum on-time $I_{PRIPEAK}$ and power limit for the specified input voltage range and output power.

The UCC28740 design calculator (SLUC487) tool facilitates the iterative calculations.

After iterating to meet the controller requirements the final results are obtained which closely matches with the calculator results.

$$L_{PRIMARY} = 856\ \mu H \quad I_{PRIPEAK} = 0.74\ A \quad I_{SCPEAK} = 4.5\ A \quad (30)$$

4.3.4 Core Selection

To keep the PCB size smaller, EE20/10/6 (EF20) Core is used. This core delivers up to 20-W power at 66 KHz as indicated in Figure 7.

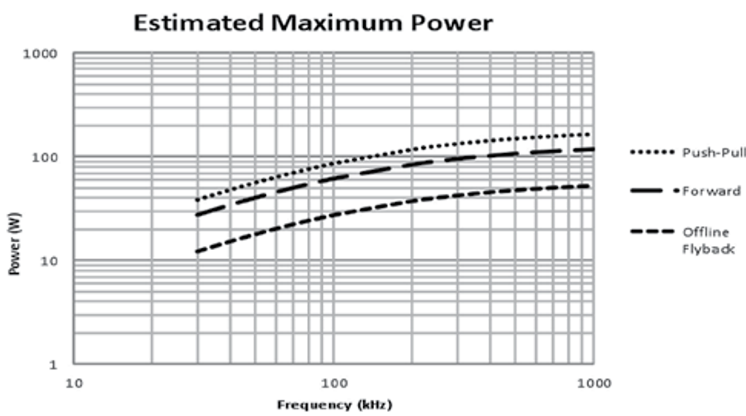


Figure 7. Power Level versus Operating Frequency for Selected Core

Given that $L_{PRIMARY}$ = 856 µH and from iteration A_L value is set for 120 nH for one gapped core and one un-gapped core.

$$N_P = \left(\frac{L_{PRIMARY}}{A_L}\right)^{1/2} = 84\,T$$

$$N_S = \frac{84}{6} = 14\,T \quad (31)$$

4.3.5 Selected Core

EE20/10/6 (EF20) from Wurth is the selected core for the transformer design. TP4A is the core material.

Table 6. Effective Core Parameters

SYMBOL	PARAMETER	VALUE	UNIT
V_e	Effective volume	1472	$–mm^3$
L_e	Effective length	46	–mm
A_e	Effective area	32	$–mm^2$

4.3.6 Flux Density (AC) Calculations

$$\beta_{ac} = \frac{V_{INDCMIN} \times T_{ONMAX}}{A_e \times N_P} \times 10^8 = 2.66 \times 10^3 \text{ Gauss} = 0.266\,T = 266\,mT$$

$$\beta_{max} = \frac{L_{PRIMARY} \times I_{PRIPEAK}}{A_e \times N_P} \times 10^8 = 0.235\,T = 235\,mT \quad (32)$$

For a flyback converter running in a discontinuous mode the AC flux density β_{ac} is equal to the maximum flux density β_{max}.

β_{max} is considered to be 270 mT max approximately.

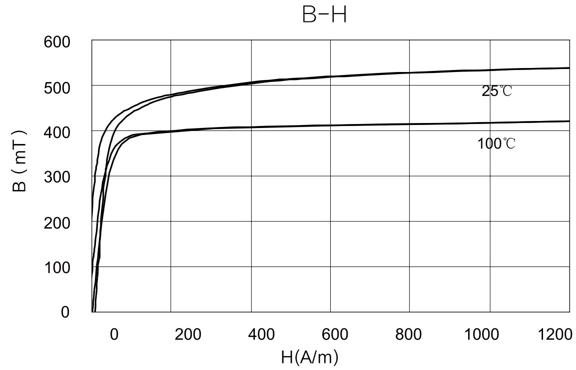


Figure 8. B-H Curve for Selected Core

Saturation point for this core is about 400 mT, so this design is about 67% of maximum value.

4.3.7 Determine Core Loss

$$\text{Bunipolar} = \beta_{ac} / 2 = 135\text{ mT} \quad (33)$$

As indicated in Figure 8 for approximately for 66 KHz curve Pcore = 70 kW/m^3

$$V_e \text{ per } m^3 = V_e / 1000^3 = 1.472 \times 10^{-6}\ m^3 \quad (34)$$

$$\text{Pcore Loss} = \text{Pcore} \times V_e \text{ per } m^3 = 70 \times 10^3 \times 1.472 \times 10^{-6}\ m^3 = 103\text{ mW} \quad (35)$$

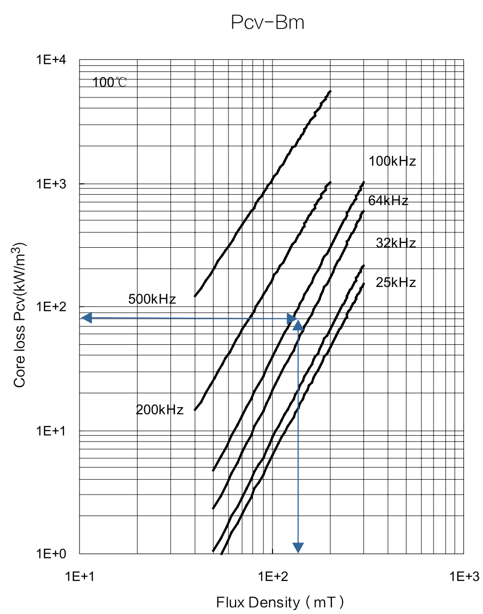


Figure 9. 4 Core Loss vs Flux Density for Selected Core at Different Operating Frequency

4.3.8 PIV Rating for Secondary's Diode

$$PIV_{SECONDARY\ DIODE} = \frac{V_{INDCMAX}}{TURN\ RATIO_S} + V_0 \quad (36)$$

- With values calculated above PIV for diodes comes to:
  - PIV is 80 V for the secondary diodes
  - Secondary peak current: 4.5 A

4.3.9 Primary MOSFET Selection

- Stress on MOSFET due to reflected voltage

$$V_{MOSFETREF} = V_{DCINMAX} + V_{OUT} \times TurnRatio_S = \sim 477\ V \quad (37)$$

- Stress due to leakage inductance

$$V_{MOSFETLKG} = Leakage\ Inductance_{Primary} \times \frac{I_{PPEAK}}{DUTYCYCLE_{MAX} \times T_{SW}} \quad (38)$$

- Considering leakage inductance to be < 5% of primary inductance value
  - $V_{MOSFETLKG} = 112.2$

$$V_{MOSFETSTRESS} = V_{MOSFETREF} + V_{MOSFETLKG} \; V_{MOSFETSTRESS} = 502.2\ V \quad (39)$$

- Peak current $I_{PEAKMOSFET} = I_{PEAK} = 0.74$ A

All other component calculations are based on TI design sheet, *UCC28740 Design Calculator Tool* (SLUC487).

Table 7 shows the calculator with actual values entered.

Table 7. Values Entered in to UCC28740 Design Calculator

DESIGN REQUIREMENTS		
Input Specifications		
Input Voltage Type, AC or DC	AC	Choose either AC or DC
Minimum Input Voltage, $V_{INPUTmin}$ =	88	VAC
Maximum Input Voltage, $V_{INPUTmax}$ =	276	VAC
Nominal Input Voltage, $V_{INPUTnom}$ =	250	VAC
Minimum Line Frequency, $f_{LINEmin}$ =	50	Hz enter 0 if DC input type
Minimum Input Voltage for Start-up, $V_{INPUTrun}$ =	80	VAC
Output Specifications		
Regulated Output Voltage, Constant Voltage Mode, V_{OUT_CV} =	15	VDC
Full Load Output Current, Constant Current Mode, I_{OCC} =	0.8	A
Target Minimum Output Voltage During Constant Current Regulation, V_{OUT_CC} =	2	VDC
Allowable Output Voltage Drop During Load-Step Transient in Constant Voltage Mode, $V_{OUT\Delta}$ =	0.7	V
Maximum Peak-to-Peak Output Voltage Ripple, V_{RIPPLE} =	150	mV
Maximum Desired Switching Frequency, f_{MAX} =	66	kHZ
Output Over-Voltage Protection, V_{OUT_OVP} =	16	V
Required Positive Load-Step Transient Current, I_{TRAN} =	0.5	A
Maximum Allowable Response Time to Load-Step Transient, t_{RESP} =	20	ms
Maximum Stand-By Power Dissipation, P_{SB} =	20	mW
Flyback Transformer, T		
Recommended Primary to Secondary Turns Ratio, N_{PS} =	6.190	Recommended N_{PS}
Actual Primary to Secondary Turns Ratio Used, N_{PS} =	6.000	Enter Actual N_{PS} Transformer Used

Table 7. Values Entered in to UCC28740 Design Calculator (continued)

DESIGN REQUIREMENTS			
Recommended Primary Inductance Value, L_P =	905.314	µH	Change R_{CS} first for Recommended L_P
Actual Primary Inductance Used, L_P =	856.000	µH	
Recommended Primary to Auxiliary Turns Ratio, N_{PA} =	1.831	Suggested N_{PA}	
Actual Primary to Auxiliary Turns Ratio, N_{PA} =	4.000	Enter Actual N_{PS} Transformer Used	
Current Sense Resistor, R_{CS}			
Recommended Current Sense Resistor, R_{CS} =	1.131	Ω	Recommended R_{CS}
Actual Current Sense Resistor Used, R_{CS} =	1.131	Ω	Enter Actual R_{CS} used
COMPONENT SELECTION USER INPUTS			
COMPONENT	**PARAMETER**		**COMMENT**
INPUT CAPACITOR, C_{BULK}			
Recommended Input Bulk Capacitance, C_{BULK} =	15.00	µF	Assumes 55% input voltage ripple
Actual Input Bulk Capacitance, C_{BULK} Used =	33.00	µF	Enter actual input bulk capacitor used
Output Rectifier, D_{OUT}			
Forward Voltage Drop of Output Rectifier, V_F =	0.7	V	Enter V_F at full load
Output Inductor, L_{OUT}			
DCR of Output Inductor, DCR_{LOUT}, if used =	0	mΩ	Enter 0 if no secondary LC filter used
MOSFET Switch, Q			
MOSFET Rated Drain to Source Voltage, V_{DS} =	650	V	
Output Capacitance of selected MOSFET, C_{OSS} =	88	pF	
Drain to Source On-Resistance of Selected MOSFET, R_{DSon} =	1.3	Ω	
MOSFET Fall Time, t_f =	33	ns	
MOSFET Turn Off Delay Time, t_{Doff} =	58	ns	
MOSFET Total Gate Charge, Q_0 =	24	nC	
Output Capacitor, C_{OUT}			
Recommended Minimum Output Capacitance, C_{OUT} =	150.000	µF	Recommended C_{OUT}
Actual Minimum Output Capacitance, C_{OUT} =	220.000	µF	Enter Actual C_{OUT} used
Recommended Maximum ESR, ESR_{COUT} =	36.578	mΩ	Recommended ESR
Actual ESR of C_{OUT} Used, ESR_{COUT} =	5.500	mΩ	Actual ESR of C_{OUT} Used
Bridge Rectifier, D_{BRIDGE}			
Forward Voltage Drop, V_{F_BRIDGE} =	0.9	V	At I_{INPEAK}
Auxiliary Winding Rectifier, D_{AUX}			
Auxiliary Rectifier Forward Voltage Drop, V_{FA} =	0.7	V	
Input Line Voltage Turn On Resistor, R_{VS1}			
Recommended Value for R_{VS1}, R_{VS1} =	105.000	kΩ	Recommended R_{VS1}
Actual Value for R_{VS1}, R_{VS1} =	110	kΩ	Enter Actual R_{VS1} Used
Output Over Voltage Resistor, R_{VS2}			
Recommended Value for R_{VS2}, R_{VS2} =	24.900	kΩ	Recommended R_{VS2}
Actual Value for R_{VS2}, R_{VS2} =	24.3	kΩ	Enter Actual R_{VS2} Used
Line Compensation Resistor, R_{LC}			
Recommended Value for R_{LC}, R_{LC} =	1.540	kΩ	Recommended R_{LC}
Actual Value for R_{LC}, R_{LC} =	1	kΩ	Enter Actual RLC Used

5 Test Setup

5.1 Equipment Used

1. Programmable DC voltage source 0 to 600 V, 0 to 5.5 A, Model TDK Lamda GEN600-5.5
2. Programmable AC voltage source 0 to 275 V, 5 A, Model California Instruments 1251P
3. Single-phase AC power analyzer Voltech PM100
4. Digital multimeter — 4-1/2 or better
5. Electronic loads, Model KIKUSUI PLZ164WA

5.2 Procedure

1. Connect the required AC or DC source to the input terminals of the PSU. Reference designator – J1.
2. Connect outputs to electronic loads. Reference designator – J2.
3. Turn on the source with no load.
4. Increase the load on 15 V output to approximately 0.8 A.

6 Test Results

6.1 Functional – Output Voltages at Different Nominal Voltages

Table 8. DC Input

V_{IN}, V DC	P_{IN}, W	$V_{01\ +15\ V}$, V	I_{O1}, A	P_O, W	Efficiency
24	18.02	14.97	0.8	12	66.58
48	16.7	14.97	0.8	12	71.84
110	15.84	14.97	0.8	12	75.76
220	15.4	14.97	0.8	12	77.92

Table 9. AC Input

V_{IN}, V AC	P_{IN}, W	$V_{01\ +15\ V}$, V	I_{O1}, A	P_O, W	Efficiency
110	15.3	14.97	0.8	12	78.43
230	14.55	14.97	0.8	12	82.47

6.2 Line Regulation

Table 10. Line Regulation — DC Input

V_{IN} – V	P_{IN} – W	V_O – V	P_O – W	Efficiency – %
21	18.25	14.97	12	65.76
22	18.08	14.97	12	66.36
23	18.17	14.97	12	66.04
24	18.02	14.97	12	66.58
48	16.7	14.97	12	71.84
110	15.84	14.97	12	75.76
150	15.6	14.97	12	76.92
220	15.4	14.97	12	77.92
250	15.5	14.97	12	77.42
300	15.6	14.97	12	76.92
320	15.36	14.97	12	78.13
340	15.3	14.97	12	78.43
350	15.4	14.97	12	77.92
360	15.48	14.97	12	77.52

Table 11. Line Regulation — AC Input

V_{IN} – V	P_{IN} – W	V_O – V	P_O – W	Efficiency – %
80	15.79	14.97	12	76
110	15.3	14.97	12	78.43
150	14.93	14.97	12	80.38
175	14.74	14.97	12	81.41
230	14.55	14.97	12	82.47
240	14.47	14.97	12	82.93
250	14.46	14.97	12	82.99
260	14.26	14.97	12	84.15
270	14.24	14.97	12	84.27

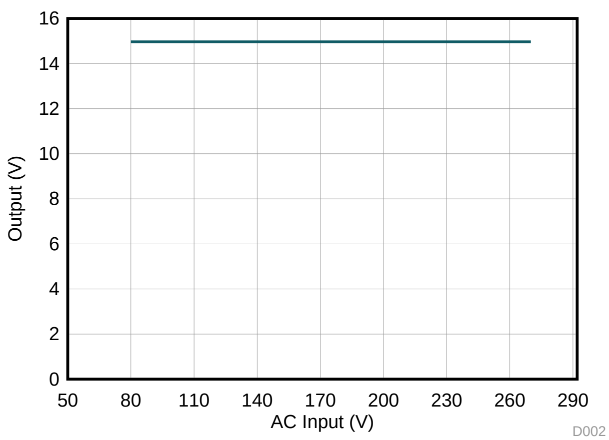


Figure 10. Output Voltage vs AC Input Voltage

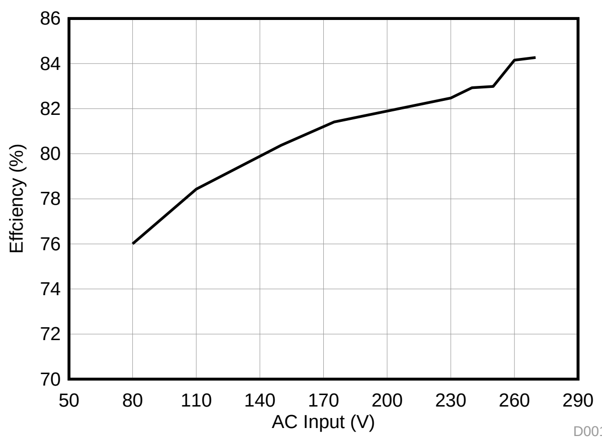


Figure 11. Efficiency vs AC Input Voltage

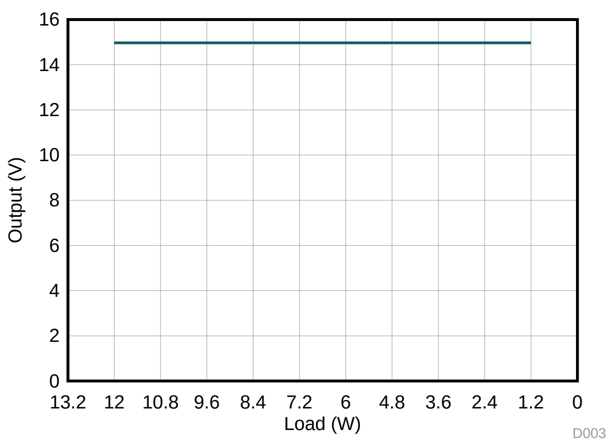


Figure 12. Load Regulation — 230-V AC Input

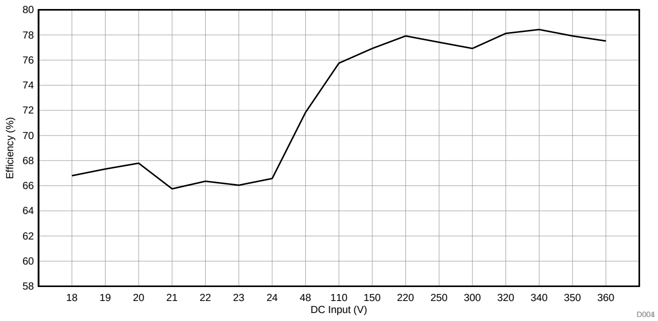


Figure 13. Efficiency vs DC Input Voltage

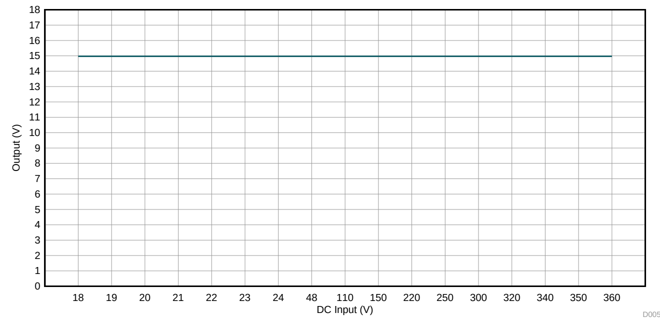


Figure 14. Line Regulation at DC Input Voltage

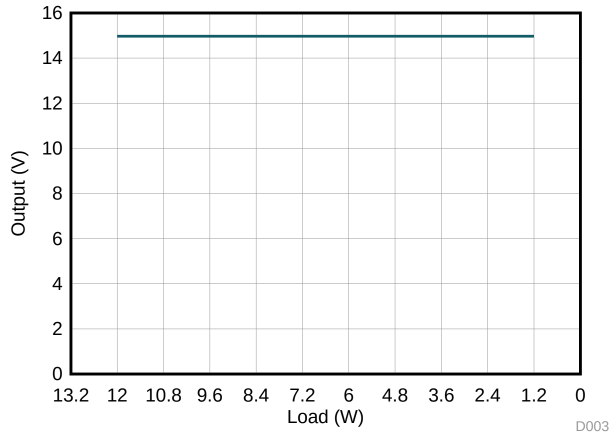


Figure 15. Load Regulation — 24-V DC Input

6.3 Load Regulation

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

Table 12. Load Regulation P_O 100% to 10% at 24-V DC Input

V_{IN} – V	P_{IN} – W	V_O – V	P_O – W
24	18	14.97	12
24	15.91	14.97	10.8
24	14.14	14.97	9.6
24	12.31	14.97	8.4
24	10.61	14.97	7.2
24	8.9	14.97	6
24	7.2	14.97	4.8
24	5.45	14.97	3.6
24	3.84	14.97	2.4
24	2.09	14.97	1.2

Table 13. Load Regulation P_O 10% to 100% at 230-V AC Input

V_{IN} – V	P_{IN} – W	V_O – V	P_O – W
230	14.55	14.97	12
230	12.95	14.97	10.8
230	11.55	14.97	9.6
230	10.08	14.97	8.4
230	8.71	14.97	7.2
230	7.28	14.97	6
230	5.91	14.97	4.8
230	4.56	14.97	3.6
230	3.12	14.97	2.4
230	1.67	14.97	1.2

6.4 Waveforms at Various Test Points as indicated

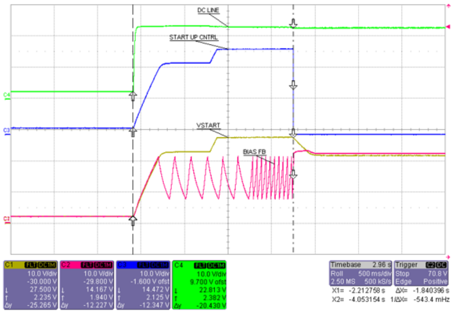


Figure 16. Start Up at 24-V DC, Full Load

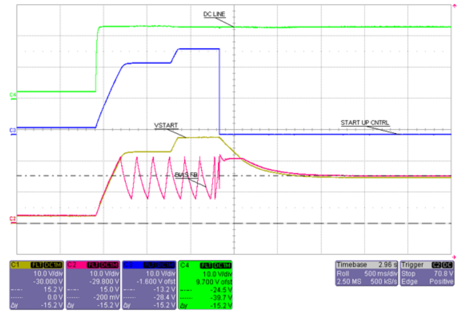


Figure 17. Start Up at 24-V DC, No Load

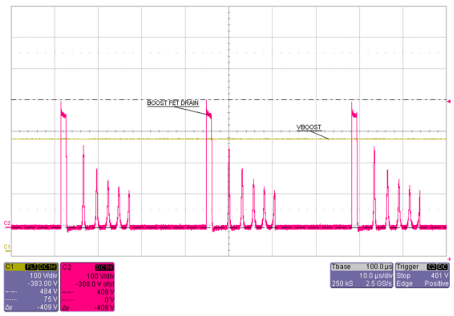


Figure 18. Booster Output V_{BOOST} and Booster FET Drain Voltage at 24-V DC Input

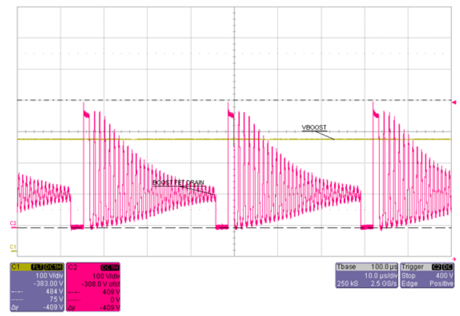


Figure 19. Booster Output V_{BOOST} and Booster FET Drain Voltage at 110-V DC Input

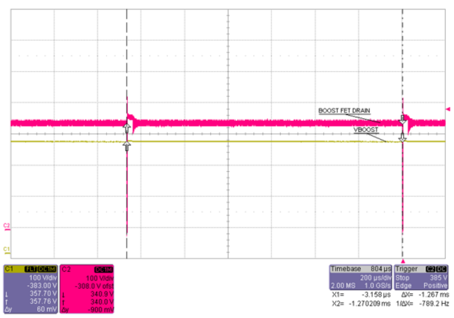


Figure 20. Booster Output V_{BOOST} and Booster FET Drain Voltage at 340-V DC Input

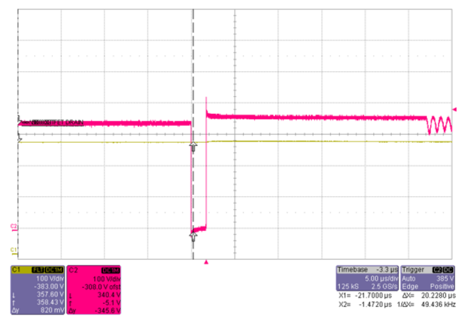


Figure 21. Booster Output V_{BOOST} and Booster FET Drain Voltage at 340-V DC Input

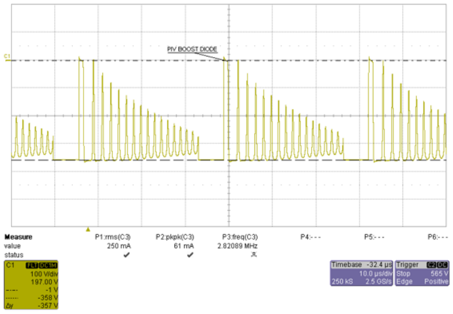


Figure 22. Booster Diode PIV at 88-V AC

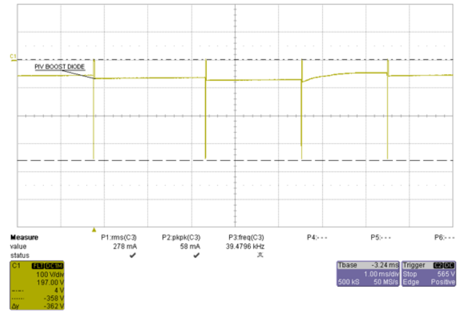


Figure 23. Booster Diode PIV at 220-V AC

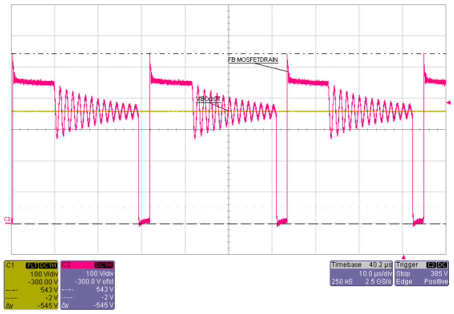


Figure 24. Booster Output V_{BOOST} and Flyback MOSFET Drain at 24-V DC

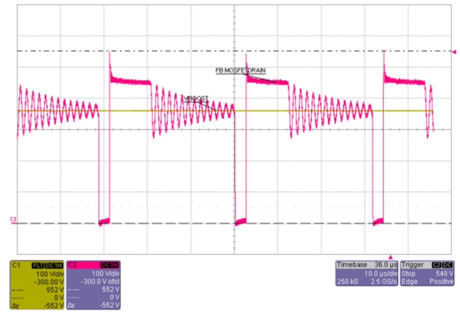


Figure 25. Booster Output V_{BOOST} and Flyback MOSFET Drain at 360-V DC

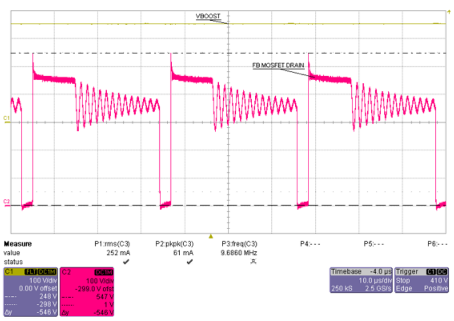


Figure 26. Booster Output V_{BOOST} and Flyback MOSFET Drain at 80-V AC

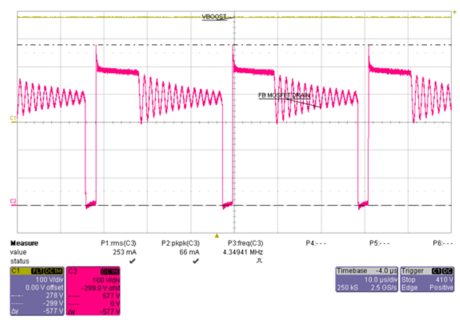


Figure 27. Booster Output V_{BOOST} and Flyback MOSFET Drain at 270-V AC

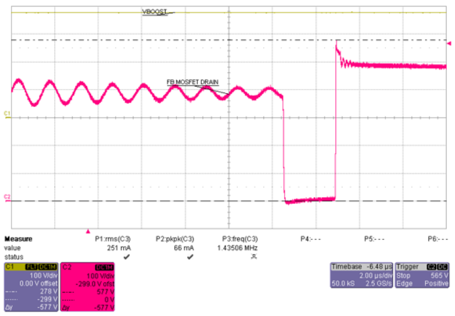


Figure 28. : Booster Output V_{BOOST} and Flyback MOSFET Drain at 270-V AC

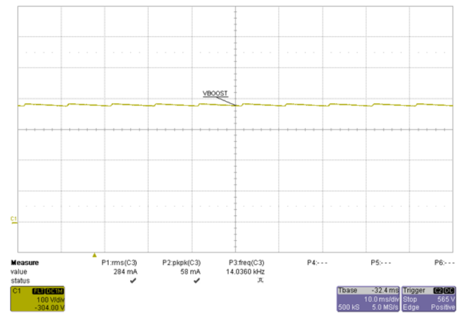


Figure 29. : Booster Output V_{BOOST} at 270-V AC

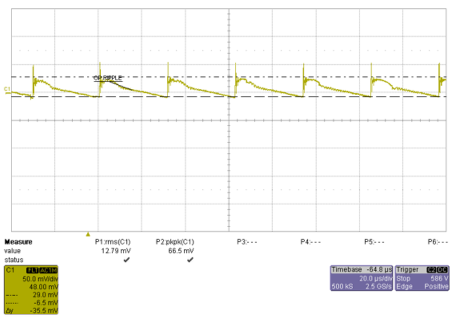


Figure 30. Output Ripple

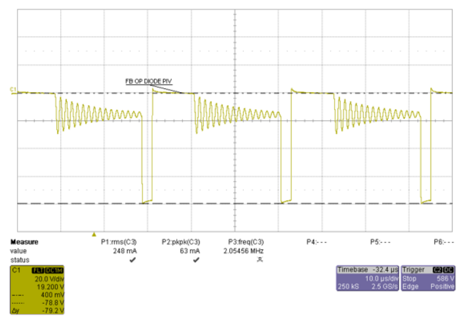


Figure 31. Flyback Secondary Diode PIV at 270-V AC

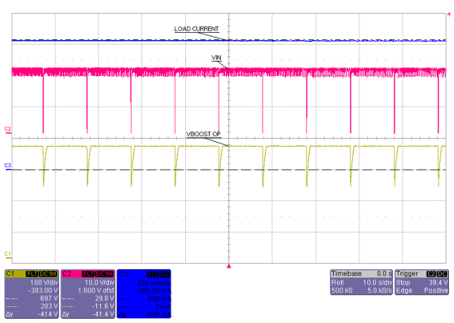


Figure 32. 100-ms Interruption at 24-V DC

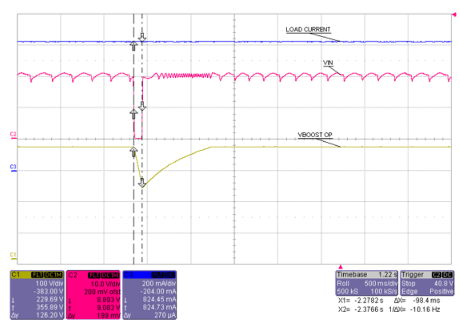


Figure 33. 100-ms Interruption at 24-V DC

6.5 EMI

This design is tested for the following EMI pre-compliance testing.

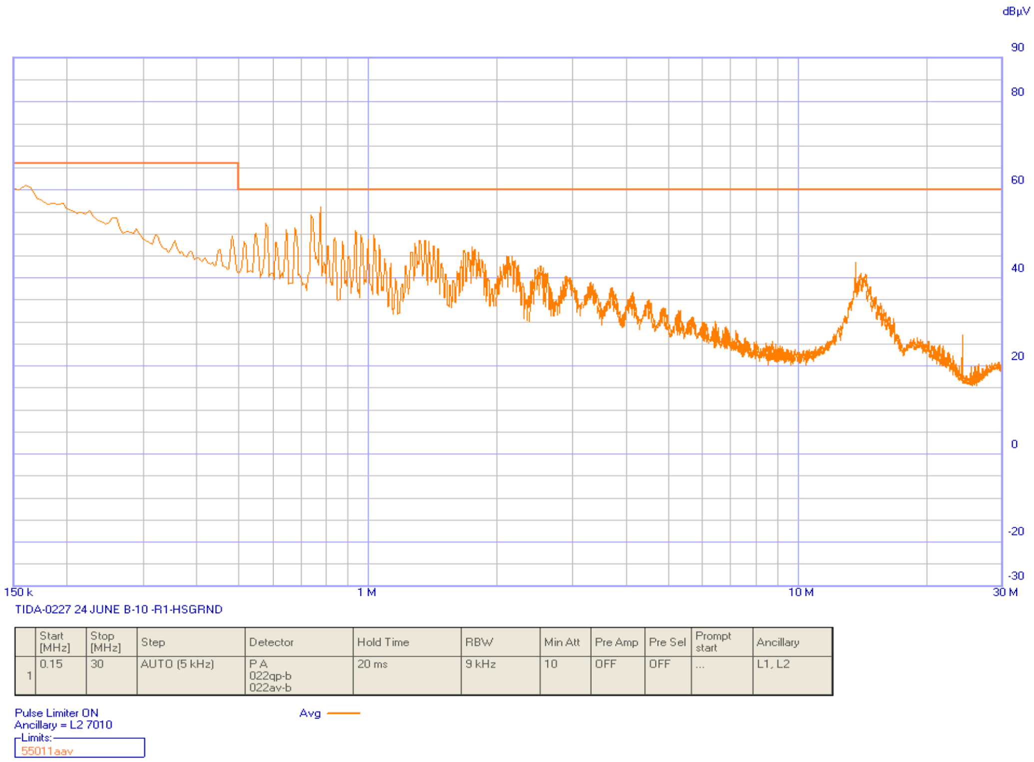


Figure 34. Test Result with Average-Mode Measurement — Tested at 230-V AC

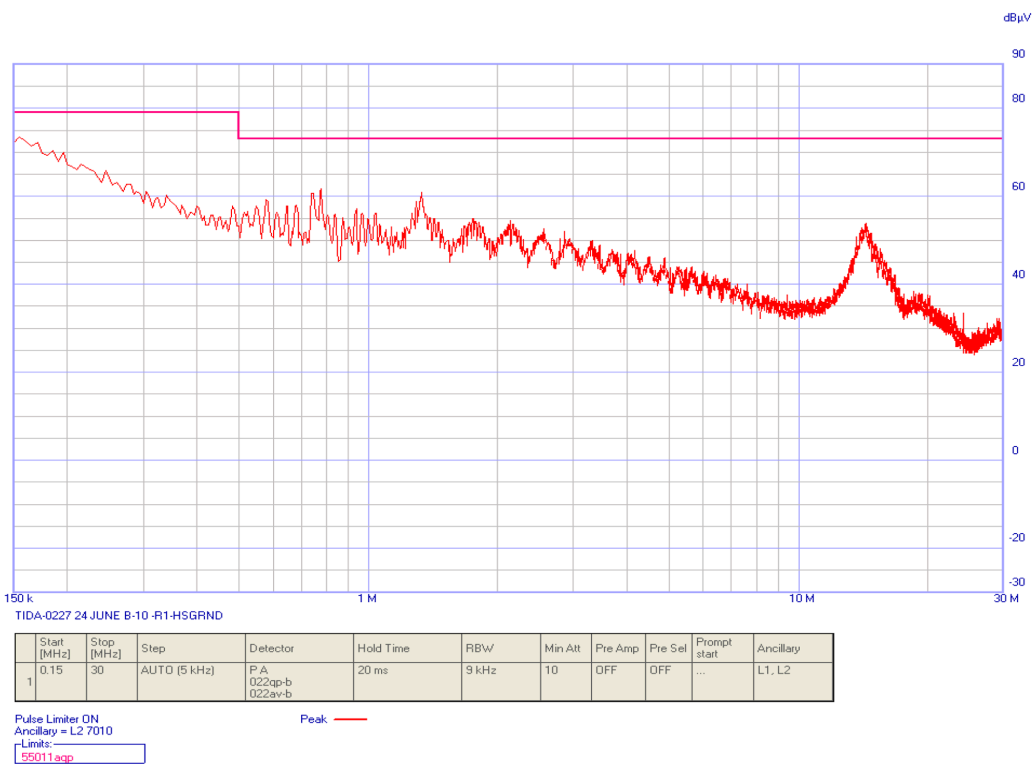


Figure 35. Test Result with Peak-Mode Measurement — Tested at 230-V AC

6.6 EMC

This design is tested for following EMC pre-compliance testing.

Table 14. EMC (Tested at 230-V AC)

TEST	APPLICABLE STANDARD	TEST LEVEL	OBSERVATION
EFT Test	IEC 61000-4-4	Level 4 kV on power port	Pass, Criteria B
Surge Test	IEC 61000-4-5	a. 2-kV differential mode b. 4-kV common mode	Pass, Criteria B

6.7 Summary of Results

Table 15. 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	65 to 77%
	80- to 276-V AC	76 to 84%
Load Regulation	10 to 100% load variation	<1%
Ripple		<100 mV peak to peak
Power Interruption Test	Dip in the output voltage <5% for time ≥100 ms after auxiliary input voltage dips to zero	Supports <100 ms interruption at 24-V DC as per IEC61000-4-29

7 Design Files

7.1 Schematics

To download the Schematics, see the design files at TIDA-00227.

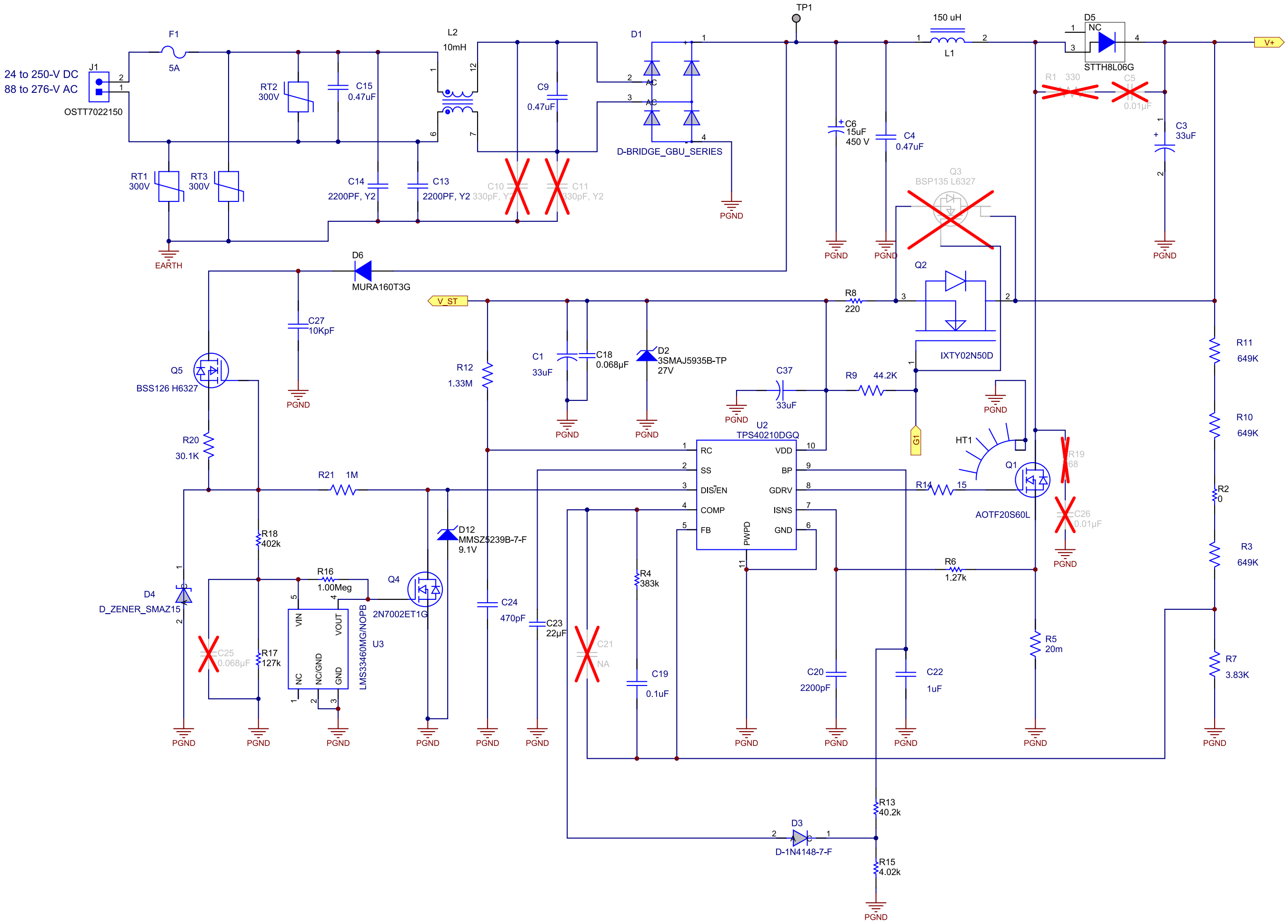


Figure 36. Schematics Page 1

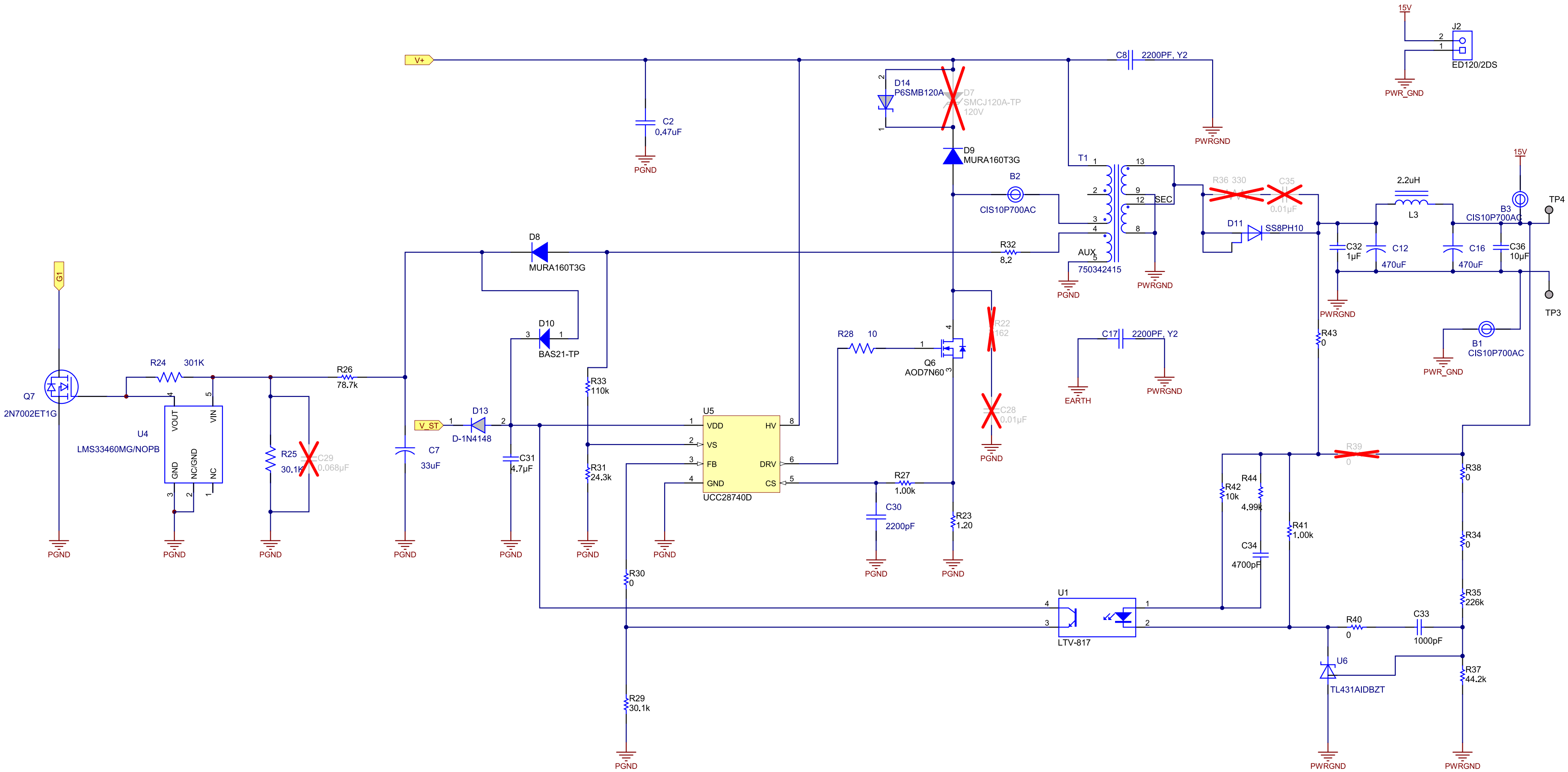


Figure 37. Schematics Page 2

7.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-00227.

Table 16. BOM

Fitted	Quantity	Designator	Description	Part Number	Manufacturer	RoHS	Package Reference
Fitted	1	!PCB1	Printed Circuit Board	TIDA-00227	Any	O	
Fitted	3	B1, B2, B3	FERRITE CHIP 70 OHM 4000MA 0603	CIS10P700AC	Samsung		
Fitted	3	C1, C7, C37	CAP ALUM 33UF 35V 20% RADIAL	35YXJ33M5X11	Rubycon		
Fitted	4	C2, C4, C9, C15	CAP FILM 0.47UF 560VDC RADIAL	R46KI347050P1M	Kemet		
Fitted	1	C3	CAP ALUM 33UF 450V 20% RADIAL	EKXG451ELL330MM20S	Nippon		18x25 mm
Fitted	1	C6	CAP ALUM 15UF 450V 20% RADIAL	EEU-EE2W150	Panasonic	Y	12.5x25
Fitted	4	C8, C13, C14, C17	CAP CER 2200PF 300VAC 20% RADIAL	VY2222M35Y5US63V7	Vishay		
Fitted	2	C12, C16	CAP ALUM 470UF 35V 20% RADIAL	EEU-FM1V471	Panasonic		
Fitted	1	C18	CAP, CERM, 0.068uF, 50V, +/-10%, X7R, 0603	GRM188R71H683KA93D	MuRata	Y	0603
Fitted	1	C19	CAP CER 0.1UF 50V 10% X7R 0603	C0603C104K5RACTU	Kemet		
Fitted	2	C20, C30	CAP, CERM, 2200pF, 50V, +/-10%, X7R, 0603	C0603C222K5RAC	Kemet		
Fitted	1	C22	CAP CER 1UF 25V 10% X7R 0603	C0603C105K3RACTU	Kemet		
Fitted	1	C23	CAP, CERM, 22uF, 16V, +/-10%, X5R, 0805	C2012X5R1C226K125AC	TDK	Y	0805
Fitted	1	C24	CAP CER 470PF 50V 5% NP0 0603	06035A471JAT2A	AVX Corporation		
Fitted	1	C27	Corporation CAP CER 10000PF 630V 10% CH 1812	C4532CH2J103K160KA	TDK Corporation		1812
Fitted	1	C31	CAP, CERM, 4.7uF, 50V, +/-10%, X5R, 0805	C2012X5R1H475K125AB	TDK	Y	0805
Fitted	1	C32	CAP, CERM, 1uF, 25V, +/-10%, X5R, 0805	08053D105KAT2A	AVX	Y	0805
Fitted	1	C33	CAP, CERM, 1000pF, 100V, +/-5%, X7R, 0603	06031C102JAT2A	AVX	Y	0603
Fitted	1	C34	CAP, CERM, 4700pF, 100V, +/-5%, X7R, 0603	06031C472JAT2A	AVX	Y	0603
Fitted	1	C36	CAP, CERM, 10uF, 25V, +/-20%, X5R, 0603	GRM188R61E106MA73	MuRata	Y	0603
Fitted	1	D1	RECT BRIDGE GPP 8A 600V GBU	GBU8J-BPMS	Micro Commercial Co		0.880 x 0.140 inch
Fitted	1	D2	Diode, Zener, 27V, 3W, SMA	3SMAJ5935B-TP	Micro Commercial Components	Y	SMA
Fitted	2	D3, D13	Diode, Signal, 300-mA, 75-V, 350-mW	1N4148W-7-F	Diodes		SOD-123
Fitted	1	D4	Diode, Zener,15-V, 1W	SMAZ15	Diodes		SMA
Fitted	1	D5	Diode, Ultrafast, 600V, 8A, DDPAK	STTH8L06G	ST Microelectronics	Y	DDPAK
Fitted	3	D6, D8, D9	Diode, Ultrafast, 600V, 1A, SMA	MURA160T3G	ON Semiconductor	Y	SMA
Fitted	1	D10	Diode, P-N, 200V, 200A, SOT-23	BAS21-TP	Micro Commercial Components	Y	SOT-23
Fitted	1	D11	Diode Schottky, 8A, 100V	SS8PH10-M3/86A	Vishay		
Fitted	1	D12	Diode, Zener, 9.1V, 500mW, SOD-123	MMSZ5239B-7-F	Diodes Inc.	Y	SOD-123
Fitted	1	D14	TVS DIODE 102VWM 165VC SMD	P6SMB120A	General		SMB
Fitted	1	F1	FUSE SLOW 250VAC 5A RADIAL	RST 5	BEL		
Fitted	1	HT1	HEATSINK TO-220 W/PINS 1.5"TALL	513102B02500G	Aavid Thermalloy		1.500x1.375in.
Fitted	1	with HT1	TO-220 Mounting Kit	4880G	Aavid Thermalloy		
Fitted	1	J1	Terminal Block, 30A, 9.52mm (.375) Pitch, 2-Pos, TH	OSTT7022150	On-Shore Technology	Y	19.62x21.5x12.5mm

Table 16. BOM (continued)

Fitted	Quantity	Designator	Description	Part Number	Manufacturer	RoHS	Package Reference
Fitted	1	J2	TERMINAL BLOCK 5.08MM VERT 2POS, TH	ED120/2DS	On-Shore Technology	Y	TERM_BLK, 2pos, 5.08mm
Fitted	1	L1	INDUCTOR 150UH 4.0A 10%	AIRD-06-151K	Abracon Corporation	Y	21 X 21 mm
Fitted	1	L2	Coupled inductor, 10mH, 5A, 0.055 ohm, TH	744825510	Wurth Elektronik eiSos	Y	30x35x21mm
Fitted	1	L3	INDUCTOR 2.2UH 4.1A RADIAL	LHL08TB2R2M	Taiyo Yuden		
Fitted	1	Q1	MOSFET, Nch, 600-V, 20A, 0.199 Ohms	AOTF20S60L	Alpha&Omega		
Fitted	1	Q2	DISCRETE, MOSFET N-CH 500V 200MA, DPAK	IXTY02N50D	IXYS	Y	–
Fitted	2	Q4, Q7	MOSFET N-CH 60V 260MA SOT-23	2N7002ET1G	OnSemi		
Fitted	1	Q5	MOSFET N-CH 600V 21MA SOT23	BSS126 H6327	Infineon		
Fitted	1	Q6	MOSFET, N-CH, 600V, 7A, DPAK	AOD7N60	AOS	Y	DPAK
Fitted	1	R2	RES, 0 ohm, 5%, 0.25W, 1206	RC1206JR-070RL	Yageo America	Y	1206
Fitted	3	R3, R10, R11	RES 649K OHM 1/4W 1% 1206 SMD	RC1206FR-07649KL	Yageo		
Fitted	1	R4	RES, 383k ohm, 1%, 0.1W, 0603	CRCW0603383KFKEA	Vishay-Dale	Y	0603
Fitted	1	R5	RES 0.02 OHM 1W 1% 2512 SMD	LRMAM2512-R02FT4	TT/Welwyn		
Fitted	1	R6	RES, 1.27k ohm, 1%, 0.1W, 0603	CRCW06031K27FKEA	Vishay-Dale	Y	0603
Fitted	1	R7	RES 3.83K OHM 1/10W 1% 0603 SMD	RC0603FR-073K83L	Yageo		
Fitted	1	R8	RES, 220 ohm, 1%, 0.1W, 0603	RC0603FR-07220RL	Yageo America	Y	0603
Fitted	1	R9	RES 44.2K OHM 1/10W 1% 0603 SMD	RC0603FR-0744K2L	Yageo		
Fitted	1	R12	RES 1.33M OHM 1/10W 1% 0603 SMD	CRCW06031M33FKEA	Vishay Dale		
Fitted	1	R13	RES, 40.2k ohm, 1%, 0.1W, 0603	CRCW060340K2FKEA	Vishay-Dale	Y	0603
Fitted	1	R14	RES 15.0 OHM 1/8W 1% 0805 SMD	RC0805FR-0715RL	Yageo		
Fitted	1	R15	RES, 4.02k ohm, 1%, 0.1W, 0603	RC0603FR-074K02L	Yageo America	Y	0603
Fitted	1	R16	RES, 1.00Meg ohm, 1%, 0.1W, 0603	CRCW06031M00FKEA	Vishay-Dale	Y	0603
Fitted	1	R17	RES, 127k ohm, 1%, 0.1W, 0603	CRCW0603127KFKEA	Vishay-Dale	Y	0603
Fitted	1	R18	RES, 402k ohm, 1%, 0.1W, 0603	CRCW0603402KFKEA	Vishay-Dale	Y	0603
Fitted	2	R20, R25	RES 30.1K OHM 1/10W 1% 0603 SMD	RC0603FR-0730K1L	Yageo		
Fitted	1	R21	RES 1.00M OHM 1/10W 1% 0603 SMD	RC0603FR-071ML	Yageo		
Fitted	1	R23	RES, 1.20 ohm, 1%, 1W, 2512	ERJ-1TRQF1R2U	Panasonic	Y	2512
Fitted	1	R24	RES 301K OHM 1/10W 1% 0603 SMD	RC0603FR-07301KL	Yageo		
Fitted	1	R26	RES, 78.7k ohm, 1%, 0.1W, 0603	CRCW060378K7FKEA	Vishay-Dale	Y	0603
Fitted	2	R27, R41	RES, 1.00k ohm, 1%, 0.1W, 0603	CRCW06031K00FKEA	Vishay-Dale	Y	0603
Fitted	1	R28	RES 10.0 OHM 1/8W 1% 0805 SMD	RC0805FR-0710RL	Yageo		
Fitted	1	R29	RES, 30.1k ohm, 1%, 0.1W, 0603	CRCW060330K1FKEA	Vishay-Dale	Y	0603
Fitted	5	R30, R34, R38, R40, R43	RES, 0 ohm, 5%, 0.1W, 0603	CRCW06030000Z0EA	Vishay-Dale	Y	0603
Fitted	1	R31	RES, 24.3k ohm, 1%, 0.1W, 0603	CRCW060324K3FKEA	Vishay-Dale	Y	0603
Fitted	1	R32	RES, 8.2 ohm, 5%, 0.75W, 2010	CRCW20108R20JNEF	Vishay-Dale	Y	2010
Fitted	1	R33	RES, 110k ohm, 5%, 0.1W, 0603	CRCW0603110KJNEA	Vishay-Dale	Y	0603
Fitted	1	R35	RES, 226k ohm, 1%, 0.1W, 0603	CRCW0603226KFKEA	Vishay-Dale	Y	0603
Fitted	1	R37	RES, 44.2k ohm, 1%, 0.1W, 0603	CRCW060344K2FKEA	Vishay-Dale	Y	0603
Fitted	1	R42	RES, 10k ohm, 5%, 0.1W, 0603	CRCW060310K0JNEA	Vishay-Dale	Y	0603

Table 16. BOM (continued)

Fitted	Quantity	Designator	Description	Part Number	Manufacturer	RoHS	Package Reference
Fitted	1	R44	RES, 4.99k ohm, 1%, 0.1W, 0603	CRCW06034K99FKEA	Vishay-Dale	Y	0603
Fitted	3	RT1, RT2, RT3	MOV, 300V	MOV-10D471KTR	Bourns		
Fitted	1	T1	TRANSFOERMER, 856uH, +/-10%, TH, 14-PIN	750342415	WURTH ELEKTRONIK	Y	–
Fitted	1	U1	Opto-Isolator, 1 Channel, TH	LTV-817	Lite-On	Y	DIP-4
Fitted	1	U2	IC REG CTRLR BST FLYBK CM 10MSOP	TPS40210DGQ	TI		
Fitted	2	U3, U4	IC DETECTOR UNDER VOLT 3V SC70-5	LMS33460MG/NOPB	TI		
Fitted	1	U5	Constant-Voltage, Constant-Current Flyback Controller Using Opto-Coupler Feedback, D0007A	UCC28740D	Texas Instruments	Y	D0007A
Fitted	1	U6	IC VREF SHUNT PREC ADJ SOT23-3	TL431AIDBZT	TI		
Fitted	8	H1, H2, H3, H4, H5, H6, H7, H8	Mounting Hole M3 3.5mm	STD	STD	Y	Screw
Not Fitted	6	FID1, FID2, FID3, FID4, FID5, FID6	Fiducial mark. There is nothing to buy or mount.	N/A	N/A		Fiducial
Not Fitted	0	C5, C26, C28, C35	CAP, CERM, 0.01uF, 1000V, +/-10%, X7R, 1210	GRM32QR73A103KW01L	MuRata	Y	1210
Not Fitted	0	C10, C11	CAP CER 330PF 300VAC 10% RADIAL	VY2331K29Y5SS63V7	Vishay		
Not Fitted	0	C21	CAP CER 470PF 50V 5% NP0 0603	06035A471JAT2A	AVX Corporation		
Not Fitted	0	C25, C29	CAP, CERM, 0.068uF, 50V, +/-10%, X7R, 0603	GRM188R71H683KA93D	MuRata	Y	0603
Not Fitted	0	D7	Diode, TVS, Uni, 120V, 1500W, SMC	SMCJ120A-TP	Micro Commercial Components	Y	SMC
Not Fitted	0	Q3	MOSFET N-CH 600V 120MA SOT-223	BSP135 L6327	Infineon		
Not Fitted	0	R1, R36	RES 330 OHM 1W 5% 2512	RC6432J331CS	Samsung		
Not Fitted	0	R19	RES 68 OHM 2W 1% 2512	RHC2512FT68R0	Stackpole Electronics Inc	Y	2512
Not Fitted	0	R22	RES 162 OHM 1.5W 1% 2512 SMD	CRCW2512162RFKEGHP	Vishay-Dale	Y	2512
Not Fitted	0	R39	RES, 0 ohm, 5%, 0.1W, 0603	CRCW06030000Z0EA	Vishay-Dale	Y	0603

Available Alternatives for BSS126:

- TSM126 N-Channel Depletion-Mode MOSFET
- KX1N60DS N-Channel Power MOSFET
- GSM501DEA 600-V N-Channel Enhancement Mode MOSFET

7.3 PCB Layout

To download the layer plots, see the design files at TIDA-00227.

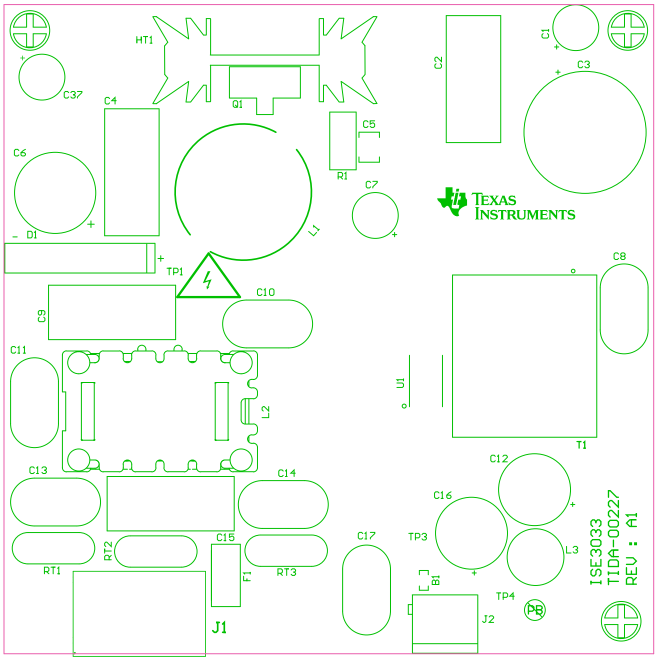


Figure 38. Silk Screen Top Overlay

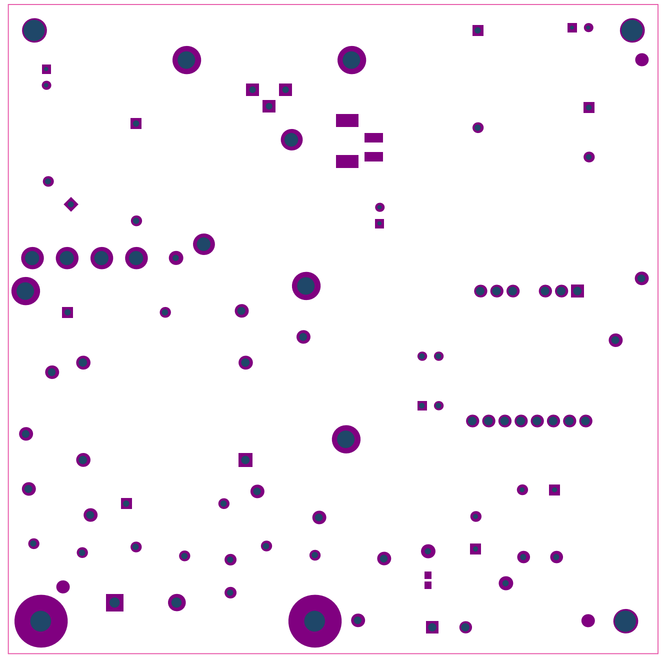


Figure 39. Top Solder Mask

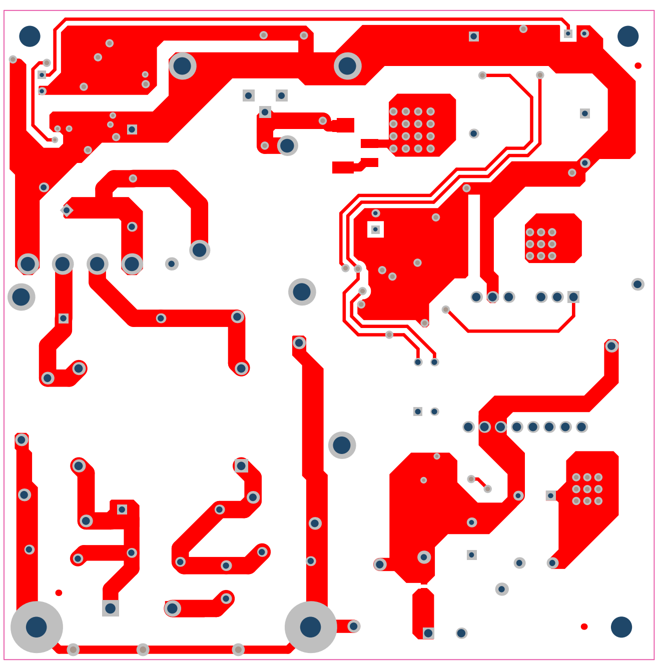


Figure 40. Top Layer

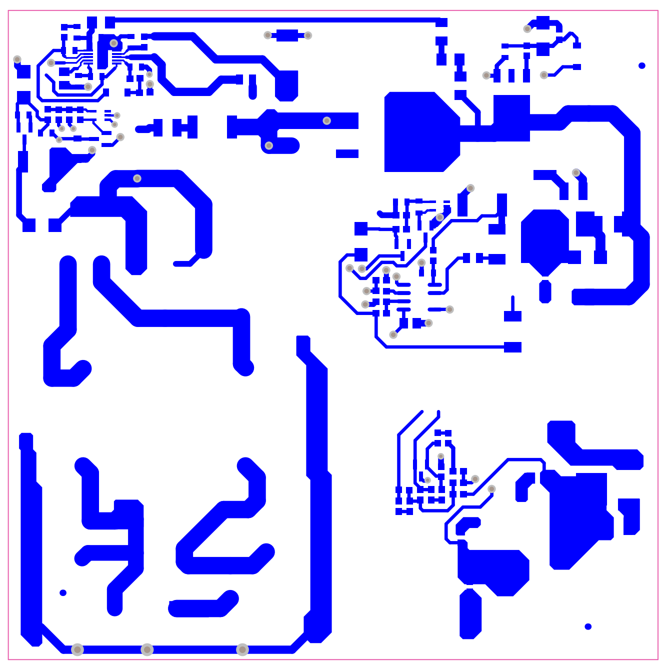


Figure 41. Bottom Layer

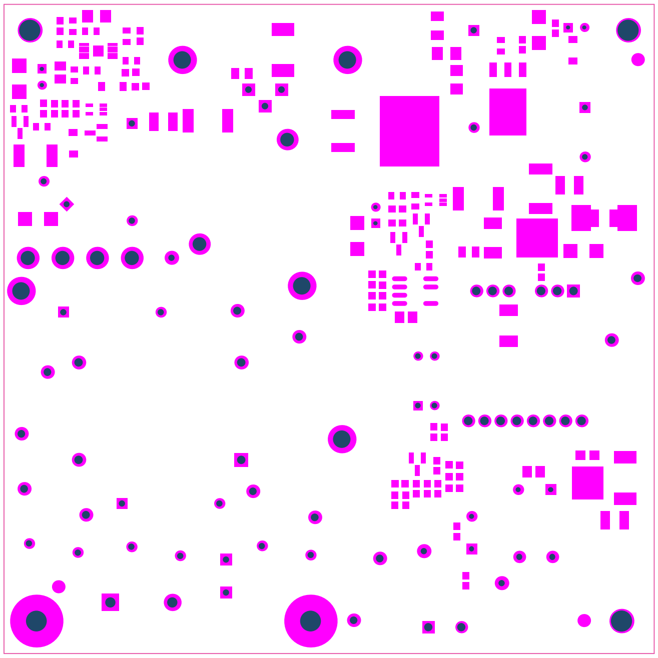


Figure 42. Bottom Solder Mask

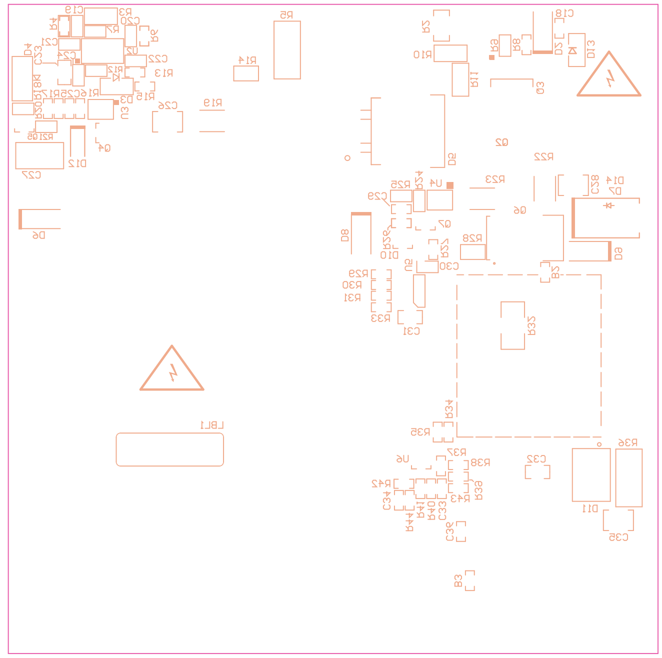


Figure 43. Bottom Overlay

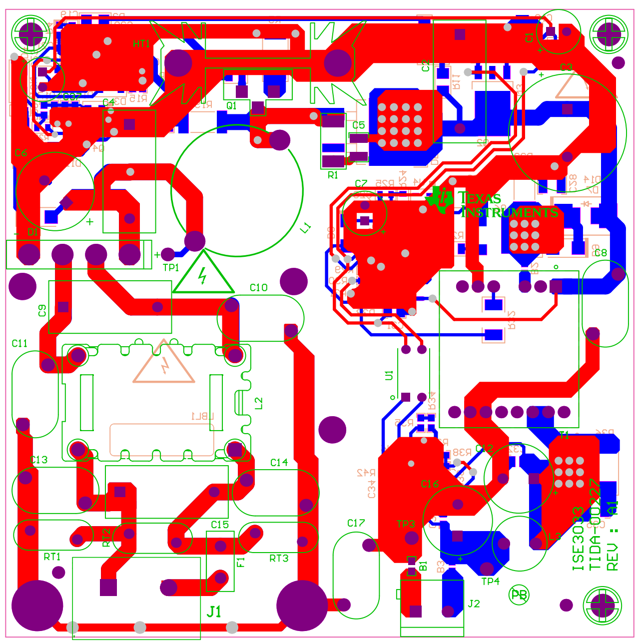
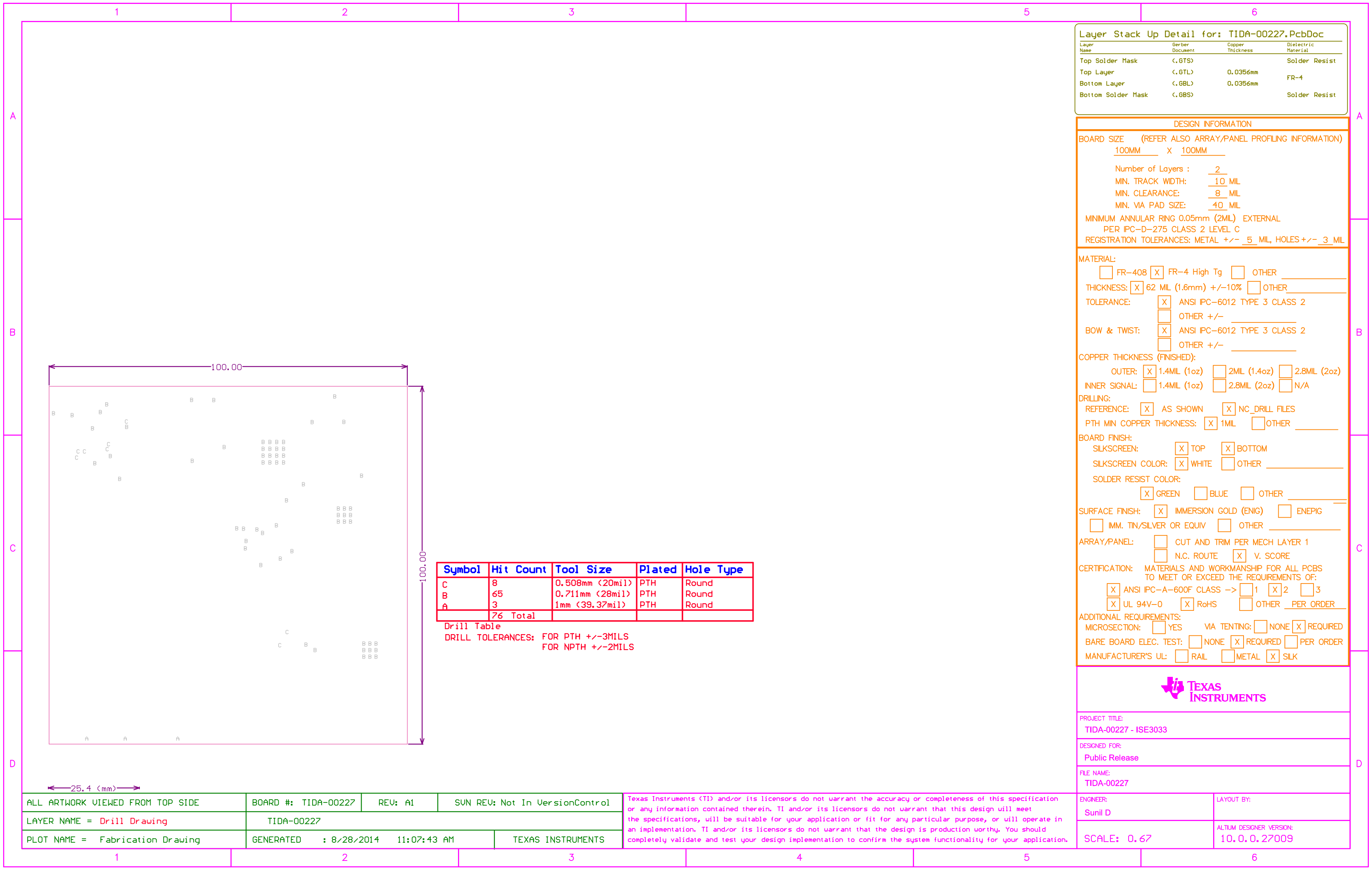


Figure 44. Multilayer Composite

7.4 Gerber Files

To download the Gerber files, see the design files at TIDA-00227.



Symbol	Hit Count	Tool Size	Plated	Hole Type
C	8	0.508mm (20mil)	PTH	Round
B	65	0.711mm (28mil)	PTH	Round
A	3	1mm (39.37mil)	PTH	Round
	76 Total			

Figure 45. Fabrication Drawing

7.5 Assembly Drawings

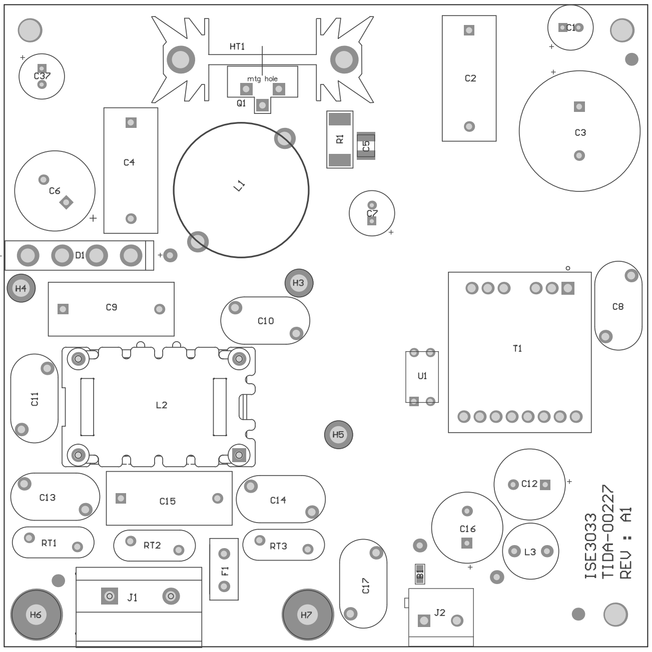


Figure 46. Top Assembly Drawing

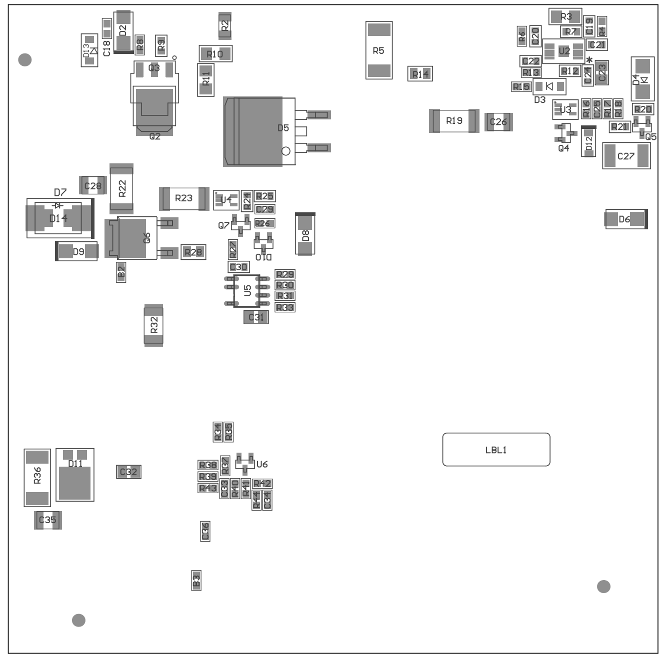


Figure 47. Bottom Assembly Drawing

7.6 Software Files

To download the software files, see the design files at TIDA-00227.

8 References

1. *TPS40210, TPS40211 4.5-V to 52-V Input Current Mode Boost Controller* (SLUS772)
2. *UCC28740 Constant-Voltage Constant-Current Flyback Controller Using Opto-Coupled Feedback* (SLUSBF3)
3. *Designing Magnetic Components for Optimum Performance in Low-Cost AC/DC Converter Applications* (SLUP265)
4. *AN-2162 Simple Success With Conducted EMI From DC-DC Converters* (SNVA489)
5. *Understanding and Optimizing Electromagnetic Compatibility in Switchmode Power Supplies* (SLUP202)
6. *Inductor and Flyback Transformer Design* (SLUP127)

9 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 (BC-E&C) from VTU, Mysore, India.

SUNIL DWIVEDI is a systems engineer at Texas Instruments where he is responsible for developing reference design solutions for the industrial segment. Sunil brings to this role his experience in high-speed digital and analog systems design. Sunil earned his bachelor of electronics (BE) in electronics and instrumentation engineering (BE-E&I) from SGSITS, Indore, India.