TI Designs

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

Design Resources

- **TIDA-00127**  Tool Folder Containing Design Files
- **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

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%
  - Load Regulation (10 to 100%) < ±3%
  - PCB Dimension 200 x 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
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.

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.
## Design Requirements

Typical power supply specifications follow.

<table>
<thead>
<tr>
<th>Functional requirement</th>
<th>Output power</th>
<th>30 W</th>
</tr>
</thead>
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<tr>
<td></td>
<td>Input voltage DC</td>
<td>24 to 250-V DC</td>
</tr>
<tr>
<td></td>
<td>Input voltage AC</td>
<td>88 to 276-V AC</td>
</tr>
<tr>
<td></td>
<td>Output voltages and load</td>
<td>12 V at 2 A, -12 V at 0.25 A, Isolated 6.75 V at 0.45 A</td>
</tr>
<tr>
<td></td>
<td>Load regulation</td>
<td>&lt; ±3%</td>
</tr>
<tr>
<td></td>
<td>Line regulation</td>
<td>&lt; ±3%</td>
</tr>
<tr>
<td></td>
<td>Output ripple</td>
<td>&lt; 200 mV pk-pk for ±12 V</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Precompliance</th>
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<tbody>
<tr>
<td></td>
<td>EFT</td>
<td>IEC 61000-4-4</td>
</tr>
<tr>
<td></td>
<td>Surge</td>
<td>IEC 61000-4-5</td>
</tr>
</tbody>
</table>

| 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 the TPS40210DGQ](image)

#### 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):
  \[ V_{\text{INDCMIN}} = 18 \text{ V} \] (1)

- Maximum DC input voltage, (V):
  \[ V_{\text{INDCMAX}} = 250 \text{ V} \] (2)

- Minimum AC input voltage, (V):
  \[ V_{\text{INACMIN}} = 80 \text{ V} \] (3)

- Maximum AC input voltage, (V):
  \[ V_{\text{INACMAX}} = 276 \text{ V} \] (4)

- Bridge rectifier drop, (V):
  \[ V_{\text{BR}} = 0.7 \text{ V} \] (5)

- Bus voltage, (V):
  \[ V_{\text{BUS}} = V_{\text{INAC}} 	imes 1.4142 - 2 	imes V_{\text{BR}} \] (6)

- Second stage output power:
  \[ P_{\text{FLYBACKOUT}} = 30 \text{ W} \] (9)

- Efficiency of booster:
  \[ \tau_{2} = 0.8 \] (10)

- Input power of booster:
  \[ P_{\text{BOOSTERIN}} = 47 \text{ W} \] (11)

- Output voltage of the booster:
  \[ V_{\text{BOOSTOUT}} = 355 \text{ V} \] (12)

- Average current of the booster:
  \[ I_{\text{BOOSTOUT}} = \frac{P_{\text{BOOSTOUT}}}{V_{\text{BOOSTOUT}}} = \frac{38}{355} = 0.106 \text{ A} \] (13)

- Output load of the Booster:
  \[ R_{\text{BOOSTOUT}} = \frac{V_{\text{BOOSTOUT}}}{I_{\text{BOOSTOUT}}} = 3361 \text{ \Omega} \] (14)

2. Preliminary Calculation

- Voltage gain of the booster:
  \[ M_{\text{MAX}} = \frac{V_{\text{BOOSTOUT}}}{V_{\text{BUS}}} = \frac{355}{16.6} = 21.39 \] (15)

  \[ M_{\text{MIN}} = \frac{V_{\text{BOOSTOUT}}}{V_{\text{BUSMAX}}} = \frac{355}{389} = 0.91 \] (16)

- Duty cycle:
  \[ D_{\text{MAX}} = 1 - \frac{1}{M_{\text{MAX}}} = 0.95 \] (17)

- Switching frequency, (Hz):
  \[ F_{\text{SW}} = 35000 \] (18)

- Time periods:
  \[ T_{\text{SW}} = 28.57 \text{ \mu s} \] (19)

- Critical inductor value to keep in discontinuous mode:
  \[ L_{\text{CRITICAL}} \leq 0.5 	imes R_{\text{BOOSTOUT}} \times T_{\text{SW}} \times D_{\text{MAX}} \times (1 \cdot D_{\text{MAX}}) \times (1 \cdot D_{\text{MAX}}) \leq 100 \text{ \mu H} \] (20)
Choose value of booster inductor:
\[ L_{\text{BOOSTER}} = 85 \, \mu \text{H} \]  
(21)

Inductor peak current, (A):
\[ I_{\text{LPEAK}} = \frac{V_{\text{RMSMIN}}}{L_{\text{BOOSTER}}} \times T_{\text{SW}} \times D_{\text{MAX}} = 5.34 \, \text{A} \]  
(22)

Inductor minimum current, (A):
\[ I_{\text{MIN}} = 0 \, \text{A} \]  
(23)

Average value of trapezoidal waveform, (A):
\[ I_{\text{PA}} = 0.5 \times (I_{\text{LPEAK}} + I_{\text{MIN}}) = 2.66 \, \text{A} \]  
(24)

DC value of trapezoidal waveform, (A):
\[ I_{\text{DC}} = D_{\text{MAX}} \times I_{\text{PA}} = 2.54 \, \text{A} \]  
(25)

RMS value of trapezoidal waveform, (A):
\[ I_{\text{RMS}} = \sqrt{D_{\text{MAX}} \times (I_{\text{LPEAK}} - I_{\text{MIN}}) \times (I_{\text{LPEAK}} - I_{\text{MIN}})} = 2.98 \, \text{A} \]  
(26)

AC value of trapezoidal waveform, (A):
\[ I_{\text{AC}} = \sqrt{I_{\text{RMS}}^2 - I_{\text{DC}}^2} = 1.57 \, \text{A} \]  
(27)

Maximum peak short circuit current:
\[ I_{\text{SCPK}} = I_{\text{LPEAK}} \times 1.2 = 6.41 \, \text{A} \]  
(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](image)

- Loss Limit considered:
\[ 300 \, \text{mW/cm}^2 = 300 \, \text{kW/m}^2 \]  
(29)

- Peak Flux density at the loss limit from the graphs at:
\[ 25 \, \text{KHz} = 0.3 \, \text{T} \]  
(30)

- Peak to Peak flux density swing:
\[ \Delta B_{\text{MAX}} = 0.6 \, \text{T} \text{ in DCM Mode} \]  
(31)

- \[ B_{\text{MAX}} = 0.28 \, \text{T} \]  
(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 \( A_w \). For a flyback converter, \( K_{PRI} \) is the ratio of the primary winding copper cross-section area to the total area.

• Area Core Product Calculation (\( A_p \)):
\[
A_p = A_w \times A_e = \left[ \frac{L_{BOOSTER} \times I_{SCPK}}{B_{MAX}} \times I_{L} \right]^{1/2} \text{cm}^4 = 0.155754144 \text{ cm}^4
\]

where
• \( L_{BOOSTER} = \) Booster Inductance
• \( I_{SCPK} = 20\% \) of \( I_{PEAK}, \text{ A} \)
• \( I_{L} = \) RMS Current, full load, A
• \( B_{MAX} = \) Saturation limited flux density, T

• Core Selected: EF25
  – Effective Volume:
  \( V_e = 2.99 \text{ cm}^3 \)
  (36)
  – Effective Length:
  \( L_e = 5.8 \text{ cm} \)
  (37)
  – Effective Area:
  \( A_e = 0.52 \text{ cm}^2 \)
  (38)

• Bobbin Details
  – Minimum Winding Width:
  \( W_w = 1.545 \text{ cm} \)
  (39)
  – Minimum Winding Height:
  \( W_h = 0.432 \text{ cm} \)
  (40)
  – Average Length of Turn:
  \( L_T = 5.28 \text{ cm} \)
  (41)
  – Winding Area:
  \( A_w = W_w \times W_h = 0.677 \text{ cm}^2 \)
  (42)
  – Area Product:
  \( A_p = A_w \times A_e = 0.347 \text{ cm}^4 \)
  (43)

5. Define \( R_T \) and Loss Limit
• Thermal resistance of core:
  \( R_T = 28 \text{ °C/W} \)
  (44)
• Maximum temperature rise:
  \( \Delta T = 50 \text{ °C} \)
  (45)
• Power loss limit based on maximum temperature rise:
  \( P_{LIM} = R_T \times \Delta T = 1.79 \text{ W} \)
  (46)
• Core Loss Limit:
  \( P_C = 0.3 \text{ W} \)
  (47)
• Winding Loss Limit:
  \( P_W = P_{LIM} \times P_C = 1.49 \text{ W} \)
  (48)
• Preliminary core loss calculation:
  \( P_C = \) Loss Limit considered \times Effective Volume = 897 mW
  (49)
6. **Calculate Maximum Number of Turns**

\[ N = \frac{L_{BOOSTER} \times I_{PEAK} \times 10^{-2}}{\Delta B_{MAX} \times A_E} = 37.42 \]  

- Actual number of turns: 
  \[ N_A = 30 \]  
- Change in the flux density due to actual number of turns: 
  \[ \Delta B_{MAX} \times \frac{N}{N_A} = 0.2910 T \]  
- Peak flux density swing: 
  \[ 0.14554 \ T \]  
- Core loss at Peak flux density: 
  \[ < 100 \text{ mW/cm}^3 \]  
- Core losses \( P_{c actual} \): 
  Core loss at Peak flux density \( \times V_E < 299 \text{ mW} \)

7. **Air Gap Calculation**

\[ l_g = \frac{0.4 \times 3.14 \times L_{BOOSTER} \times I_{PEAK}^2 \times 10^6}{A_E \times B_{MAX}^2 \times 10^6} \times 10^3 = 0.1076 \text{ cm} = 1.1 \text{ mm} \]

8. **Calculate the Conductor Size**

- Minimum winding width: 
  \[ B_w = 1.545 \text{ cm} \]  
- Height: 
  \[ H_w = 0.432 \text{ cm} \]  
- Creepage allowance: 
  \[ C_{ma} = 0.3 \text{ cm} \]  
- Actual winding width possible: 
  \[ B_{wa} = B_w - 2 \times C_{ma} = 0.945 \text{ cm} \]  
- Current Density: 
  \[ J_{MAX} = 450 \text{ A/cm}^2 \]  
- Wire size required: 
  \[ \text{Conductor Area} = \frac{\text{RMS Current}}{\text{Current Density}} = 0.006673138 \text{ cm}^2 \]

**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](image)

10. Output Diode Selection

- Using 80% dating on \( V_{\text{OUT}} \) for ringing on the switch node. The rectifier diode minimum reverse breakdown voltage is given by:
  \[
  V_{\text{FWDIODE}} \geq 1.25 \times V_{\text{BOOSTOUT}} \geq 488 \text{ V}
  \]
  (67)
- The diode must have a reverse breakdown voltage greater than 500 V. The rectifier diode peak and average currents are estimated by:
  \[
  I_{\text{BD(avg)}} = I_{\text{BOOSTOUT}} = 0.096 \text{ A}
  \]
  (68)
  \[
  I_{\text{BD(PEAK)}} = I_{\text{LPEAK}} = 5.34 \text{ A}
  \]
  (69)
- The power dissipation in the diode is estimated by:
  \[
  P_{\text{BDiode}} = I_{\text{BD(avg)}} \times V_{F} = 0.067 \text{ W}
  \]
  (70)

### Table 1. Output Diode Selection

<table>
<thead>
<tr>
<th>Part Number</th>
<th>Type of Diode</th>
<th>PIV</th>
<th>IF</th>
<th>Surge Current Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>MUR460</td>
<td>Ultrafast</td>
<td>600 V</td>
<td>4 A</td>
<td>150 A</td>
</tr>
</tbody>
</table>

11. Output Capacitor Selection

\[
C_{\text{OUT}} = \frac{(8 \times I_{\text{BOOSTOUT}} \times D_{\text{MAX}})}{(V_{\text{BOOSTOUT RIPPLE}} \times F_{\text{SW}})}
\]
(71)
\[
V_{\text{BOOSTOUT RIPPLE}} = 0.5 \text{ V}
\]
(72)
\[
C_{\text{OUT}} \text{ with 20\% tolerance} = 50 \mu F
\]
(73)
\[
ESR_{C_{\text{OUT}}} = \frac{(7 \times V_{\text{BOOSTOUT RIPPLE}})}{(8 \times (I_{\text{LPEAK}} - I_{\text{BOOSTOUT}})} = 0.083 \Omega
\]
(74)

### Table 2. Output Capacitor Selection

<table>
<thead>
<tr>
<th>SELECTED ( C_{\text{OUT}} )</th>
<th>68</th>
<th>( \mu F )</th>
<th>450</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>PART NUMBER</td>
<td>EKXG451ELL680MMN3S</td>
<td>United Chemicon</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
12. Current Sense and Current Limit

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

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

$$V_{\text{ISNS(OC)}} = 0.15 \text{ V}$$

$R_{\text{ISNS}}$ is approximately 30 m$\Omega$

- Power Dissipation in the current sense resistor:

$$P_{\text{ISNS}} = I_{\text{RMS}}^2 \times R_{\text{ISNS}} \times D_{\text{MAX}}$$

An approximately 1-W resistor is chosen

13. Soft Start Capacitor

The capacitor on the SS terminal $C_{\text{SS}}$ 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:

$$C_{\text{SS}} = \frac{t_{\text{SS}}}{R_{\text{SS(chg)}} \times \ln \left( \frac{V_{\text{BP}} - V_{\text{SS(ofst)}}}{V_{\text{BP}} - (V_{\text{SS(ofst)}} + V_{\text{FB}})} \right)}$$

$$t_{\text{SS}} > C_{\text{OUT}} \times \frac{V_{\text{BP}}}{I_{\text{OUT(OC)}} - I_{\text{EXT}}}$$

where

- $I_{\text{C(Chg)}}$ is the output capacitor charging current in A
- $C_{\text{OUT}}$ is the total output capacitance in F
- $V_{\text{OUT}}$ is the output voltage in V
- $t_{\text{SS}}$ is the soft start time
- $I_{\text{OUT(OC)}}$ is the desired overcurrent trip point in A
- $I_{\text{EXT}}$ is any external load current in A
- $R_{\text{SS(chg)}}$ is the SS charging resistance in $\Omega$, typically 500 k$\Omega$
- $C_{\text{SS}}$ is the value of the capacitor on the SS terminal, in F
- $V_{\text{BP}}$ is the value of the voltage on BP terminal, in V
- $V_{\text{SS(ofst)}}$ is the approximate level shift from the SS terminal to the error amplifier (approximately 700 mV)
- $V_{\text{FB}}$ is the error amplifier reference voltage, 700 mV typical
- Considering $I_{\text{EXT}} = 0.10$ A and $I_{\text{OUT(OC)}} = 0.12$A, $t_{\text{SS}}$ is 1.37 seconds and $C_{\text{SS}} = 22 \mu$F
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).
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:
     \[ V_{\text{INDCMIN}} = 90 \]  
     \[ V_{\text{INDCMAX}} = 355 \]  

   • Output voltage-01, V:
     \[ V_{01} = 12 \]  
     \[ I_{01} = 2.0 \text{ A} \]  

   • Output voltage-02, V:
2. Preliminary Calculation

- Efficiency of Flyback Converter:
  \( \tau_2 = 0.8 \)
  \( \) (90)

- Primary Input Power, W:
  \( P_{\text{in}} = \frac{P_{\text{out}}}{\tau_2} = 39.23 \text{ W} \)
  \( \) (91)

- Primary Duty Cycle:
  \( D_p = 0.49 \)
  \( \) (92)

- Secondary Duty Cycle:
  \( D_S = 0.51 \)
  \( \) (93)

- Turns Ratio for secondary winding \( V_{01}, V_{02} \):
  \[ N = \frac{V_{00}}{N \cdot V_{01} + V_{02}} \cdot \frac{D_S}{1 - D_p} = 6.86 \]
  \( \) (94)

- Actual Turn Ratio:
  \( N_A = 7 \)
  \( \) (95)

- Turn Ratio for Isolated Winding:
  \( V_{03} = 11.6 \rightarrow 12 \)
  \( \) (96)

- Actual Duty Cycle:
  \( D_A = \frac{(V_{01} + V_{02}) \times N_A}{V_{00} + (V_{01} + V_{02}) \times N_A} = 0.495 \)
  \( \) (97)

- \( D_{SA} \):
  \( 1 - D_{SA} = 0.51 \)
  \( \) (98)

- Current Calculation (Secondary Peak Current):
  \( I_{\text{SCP}} = 2 \times \frac{I_{\text{lDC}}}{D_{SA}} \)
  \( \) (99)

  where
  - \( I_{\text{lDC}} = \) Output Current \( I_0 \)
    - Secondary-01 Peak Current \( I_{01\text{PK}} = 7.92 \text{ A} \)
    - Secondary-02 Peak Current \( I_{02\text{PK}} = 0.99 \text{ A} \)
    - Secondary-03 Peak Current \( I_{03\text{PK}} = 2.48 \text{ A} \)

- Secondary RMS Current:
  \[ I_{\text{rms}} = \sqrt{D_{SA} \times \frac{I_{\text{SCP}}^2}{3}} \]
  \( \) (100)

  where
  - \( I_{\text{SCP}} \) is the respective secondary peak current \( I_{\text{PK}} \)
  - Secondary-01 RMS Current: \( I_{01\text{rms}} = 3.25 \text{ A} \)
  - Secondary-02 RMS Current: \( I_{02\text{rms}} = 0.41 \text{ A} \)
  - Secondary-03 RMS Current: \( I_{03\text{rms}} = 1.02 \text{ A} \)
\[ I_{\text{AC}} = \sqrt{(I_{\text{rms}} - I_{\text{DC}})} \]

where

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

- Primary Average Current:
  \[ I_{\text{P AVG}} = \frac{P_{\text{IN}}}{V_{\text{DC MIN}}} = 0.44 \ A \]  

- Primary Peak Current:
  \[ I_{\text{P P EAK}} = 2 \times \frac{I_{\text{rmsAC}}}{D_{\text{P N}}} = 1.85 \ A \]

- Primary Inductance Required:
  \[ L_{p} = \frac{V_{\text{DC MIN}} \times N_{p} \times D_{\text{P A}}}{I_{\text{P P EAK}}} = 480 \ \mu\text{H} \]

- Inductor Minimum Current, A
  \[ I_{\text{MIN}} = 0 \ A \]

- Average Value of Trapezoidal Waveform, A:
  \[ I_{\text{P A}} = 0.5 \times (I_{\text{P P EAK}} + I_{\text{MIN}}) = 0.93 \ A \]

- DC Value of Trapezoidal waveform, A:
  \[ I_{\text{DC}} = D_{\text{MAX}} \times I_{\text{P A}} = 0.464 \ A \]

- RMS Value of Trapezoidal Waveform, A:
  \[ I_{\text{RMS}} = \sqrt{D_{\text{MAX}} \times \left( (I_{\text{P P EAK}} \times I_{\text{MIN}}) + (I_{\text{P P EAK}} - I_{\text{MIN}}) \times (I_{\text{P P EAK}} - I_{\text{MIN}}) \right)} = 0.75 \ A \]

- AC Value of Trapezoidal Waveform, A:
  \[ I_{\text{AC}} = \sqrt{I_{\text{RMS}}^2 - I_{\text{DC}}^2} = 0.60 \ A \]

- Max Peak Primary Short Circuit Current:
  \[ I_{\text{P P EAK}} = I_{\text{P P EAK}} \times 1.1 = 2.0 \ A \]

3. Select Core Material TP4A

4. Determine Max Flux Density and Max Flux Swing

![Figure 7. Flux Density (mT) versus Core Power Loss (kW/m³)](image)

- Loss Limit considered:
  \[ 300 \, \text{mW/cm}^2 = 300 \, \text{kW/m}^3 \]
• Peak Flux density at the loss limit from the graphs at:
  100 KHz = 0.11 T (considered)  
(112)
• Peak to Peak flux density swing:
  ∆B_{\text{MAX}} = 0.22 T in DCM Mode ∆B_{\text{MAX}} = B_{\text{MAX}}  
(113)
• B_{\text{MAX}} = 0.22 T
• Constant K1 = 0.085

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

• Area Core Product Calculation (A_p):
  \[ A_p = A_w \times A_e = \left[ \frac{L_p}{B_{\text{MAX}}} \times \frac{I_{\text{SCPk}}}{K_1} \times I_{\text{L}} \right]^{\frac{1}{2}} \text{cm}^4 = 0.288952 \text{cm}^4 \]  
(116)

where
• \( L_p \) = Primary Inductance
• \( I_{\text{SCPk}} \) = 10% of \( I_{\text{LPEAK}} \) A
• \( I_{\text{L}} \) = RMS Current, full load, A
• \( B_{\text{MAX}} \) = Saturation limited flux density, T

• Core Selected: ER28/14
  – Effective Volume:
    \( V_e = 5.2544 \text{ cm}^3 \)  
(118)
  – Effective Length:
    \( L_e = 6.4 \text{ cm} \)  
(119)
  – Effective Area:
    \( A_e = 0.821 \text{ cm}^2 \)  
(120)

• Bobbin Details
  – Minimum Winding Width:
    \( W_w = 1.661 \text{ cm} \)  
(121)
  – Minimum Winding Height:
    \( W_h = 0.439 \text{ cm} \)  
(122)
  – Average Length of Turn:
    \( L_T = 5.28 \text{ cm} \)  
(123)
  – Winding Area:
    \( A_w = B_w \times H_w = 0.729179 \text{ cm}^2 \)  
(124)
  – Area Product:
    \( A_p = A_w \times A_e = 0.598656 \text{ cm}^4 \)  
(125)

• Mean Length per Turn:
  \( \text{MLT} = 3.83 \text{ cm} \)  
(126)

5. Define \( R_t \) and Loss Limit
• Thermal resistance of core:
  \( R_t = 28.75 \text{ °C/W} \)  
(127)
• Maximum temperature rise:
  \( \Delta T = 50 \text{ °C} \)  
(128)
• \( P_{\text{lim}} \):
  \( ^\circ \text{C Rise} / R_t = 1.73913 \text{ W} \)  
(129)
• Preliminary core loss calculation:
6. Calculate Number of Turns

\[ N = \frac{(I_e \times I_{\text{PEAK}} \times 10^2)}{\Delta B_{\text{MAX}} \times A_e} = 49.32 \]  

- 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: \( N_{S03} = 4.3 \rightarrow 4 \)
- Change in the \( \Delta B_{\text{MAX}} \) due to the round off of:
  \[ N_f = \Delta B_{\text{MAX}} \times \frac{N}{N_A} = 0.22 T \]  
- 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

\[ l_g = \frac{(0.4 \times 3.14 \times L_p \times I^2_{\text{PEAK}} \times 10^4)}{A_e \times B^2_{\text{MAX}} \times 10^3} = 0.0521968 \text{ cm} = 0.52197 \text{ mm} \]

8. Calculate the Conductor Size and Winding Resistance

- Minimum winding width:
  \( B_w = 1.661 \text{ cm} \)
- Height:
  \( H_w = 0.439 \text{ cm} \)
- Creepage allowance:
  \( C_A = 0.3 \text{ cm} \)
- Actual winding width possible:
  \( B_{wa} = B_w - 2 \times C_a = 1.061 \text{ cm} \)
- Current density:
  \( J_{\text{MAX}} = 450 \text{ A/cm}^2 \)
- Wire size required:
  \[ \text{Conductor Area} = \frac{RMS \text{ Current}}{Current \text{ Denisty}} \]  
- Wire size for output-01:
  \( W_{01} = 0.72 \text{ mm}^2 \)
- Wire size for output-02:
  \( W_{02} = 0.09 \text{ mm}^2 \)
- Wire size for output-03:
  \( W_{03} = 0.14 \text{ mm}^2 \)
- Wire size for primary \( W_p \):
  \( W_p = 0.16 \text{ mm} \)
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

\[
P[IV]_{SECONdARY\ diode} = \frac{V_{IN}^{MAX}}{TURN\ RATIO} + V_0
\]

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

10. Primary MOSFET Selection

- Stress on MOSFET due to reflected voltage:
  \[
  V_{MOSFETREF} = V_{DCIN}^{MAX} + V_{OC} \times Turn\ Ratio, \approx 477\ V
  \]

- Stress due to leakage inductance:
  \[
  V_{MOSFETLKG} = \frac{Leakage\ Inductance_{primary} \times I_{PEAK}}{DUTYCycLE_{MAX} \times T_{sw}}
  \]

- Considering leakage inductance to be 2% of Primary inductance value:
  \[
  V_{MOSFETLKG} = 91.8\ V
  \]
  \[
  V_{MOSFETSTRESS} = V_{MOSFETREF} + V_{MOSFETLKG}
  \]
  \[
  V_{MOSFETSTRESS} = 568.3
  \]
- Peak Current:
  \[
  I_{PEAKMOSFET} = I_{PEAK} = 2\ A
  \]
- RMS Current:
  \[
  I_{RMSMOSFET} = I_{RMS} = 0.7\ A
  \]
Table 4. MOSFET Rating (AOTF4S60)

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>RATING</th>
<th>UNITS</th>
<th>SYMBOL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drain-Source Voltage</td>
<td>600</td>
<td>V</td>
<td>V_{DS}</td>
</tr>
<tr>
<td>Continuous Drain Current at 25C</td>
<td>4</td>
<td>A</td>
<td>I_D</td>
</tr>
<tr>
<td>Continuous Drain Current at 100C</td>
<td>3.7</td>
<td>A</td>
<td>I_D</td>
</tr>
<tr>
<td>Pulsed Drain Current</td>
<td>16</td>
<td>A</td>
<td>I_{DM}</td>
</tr>
<tr>
<td>RDS(On) Max</td>
<td>0.9</td>
<td>Ω</td>
<td></td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>V_{IN}, V DC</th>
<th>P_{IN}, W</th>
<th>V_{01} + 12 V, V</th>
<th>I_{01}, A</th>
<th>V_{02} – 12 V, V</th>
<th>I_{02}, A</th>
<th>V_{03} + 6.75 V, V</th>
<th>I_{03}, A</th>
<th>P_{O}, W</th>
<th>EFFICIENCY</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>46.8</td>
<td>12.04</td>
<td>2</td>
<td>–11.99</td>
<td>0.25</td>
<td>6.89</td>
<td>0.450</td>
<td>30</td>
<td>63.75</td>
</tr>
<tr>
<td>24.0</td>
<td>46.2</td>
<td>12.03</td>
<td>2</td>
<td>–11.98</td>
<td>0.25</td>
<td>6.88</td>
<td>0.450</td>
<td>30</td>
<td>64.48</td>
</tr>
<tr>
<td>110</td>
<td>39.8</td>
<td>12.04</td>
<td>2</td>
<td>–11.99</td>
<td>0.25</td>
<td>6.89</td>
<td>0.450</td>
<td>30</td>
<td>74.92</td>
</tr>
<tr>
<td>220</td>
<td>38.5</td>
<td>12</td>
<td>2</td>
<td>–11.99</td>
<td>0.25</td>
<td>6.89</td>
<td>0.450</td>
<td>30</td>
<td>77.28</td>
</tr>
</tbody>
</table>

Table 6. AC Input

<table>
<thead>
<tr>
<th>V_{IN}, V AC</th>
<th>P_{IN}, W</th>
<th>V_{01} + 12 V, V</th>
<th>I_{01}, A</th>
<th>V_{02} – 12 V, V</th>
<th>I_{02}, A</th>
<th>V_{03} + 6.75 V, V</th>
<th>I_{03}, A</th>
<th>P_{O}, W</th>
<th>EFFICIENCY</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>42.33</td>
<td>12.04</td>
<td>2</td>
<td>–11.96</td>
<td>0.25</td>
<td>6.88</td>
<td>0.450</td>
<td>30</td>
<td>70.45</td>
</tr>
<tr>
<td>220</td>
<td>39.22</td>
<td>12.04</td>
<td>2</td>
<td>–11.99</td>
<td>0.25</td>
<td>6.88</td>
<td>0.450</td>
<td>30</td>
<td>76.06</td>
</tr>
<tr>
<td>250</td>
<td>38.37</td>
<td>12.04</td>
<td>2</td>
<td>–11.98</td>
<td>0.25</td>
<td>6.89</td>
<td>0.450</td>
<td>30</td>
<td>77.75</td>
</tr>
</tbody>
</table>
6.2 Line Regulation

Table 7. Line Regulation DC Supply

<table>
<thead>
<tr>
<th>V_{in}, V DC</th>
<th>I_{in}, A</th>
<th>P_{in}, W</th>
<th>V_{01}, V DC</th>
<th>I_{01}, A</th>
<th>V_{02}, V DC</th>
<th>I_{02}, A</th>
<th>V_{03}, V DC</th>
<th>I_{03}, A</th>
<th>P_{out}, W</th>
<th>EFFICIENCY</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>2.34</td>
<td>46.8</td>
<td>12.04</td>
<td>2</td>
<td>-11.99</td>
<td>0.25</td>
<td>6.89</td>
<td>0.45</td>
<td>30</td>
<td>63.75</td>
</tr>
<tr>
<td>20.2</td>
<td>2.34</td>
<td>47.3</td>
<td>12.04</td>
<td>2</td>
<td>-11.99</td>
<td>0.25</td>
<td>6.89</td>
<td>0.45</td>
<td>30</td>
<td>63.12</td>
</tr>
<tr>
<td>22.0</td>
<td>2.115</td>
<td>46.5</td>
<td>12.04</td>
<td>2</td>
<td>-11.98</td>
<td>0.25</td>
<td>6.89</td>
<td>0.45</td>
<td>30</td>
<td>64.11</td>
</tr>
<tr>
<td>24.0</td>
<td>1.926</td>
<td>46.3</td>
<td>12.03</td>
<td>2</td>
<td>-11.98</td>
<td>0.25</td>
<td>6.88</td>
<td>0.45</td>
<td>30</td>
<td>64.48</td>
</tr>
<tr>
<td>48</td>
<td>0.882</td>
<td>42.3</td>
<td>12.04</td>
<td>2</td>
<td>-11.99</td>
<td>0.25</td>
<td>6.89</td>
<td>0.45</td>
<td>30</td>
<td>70.47</td>
</tr>
<tr>
<td>72</td>
<td>0.567</td>
<td>40.8</td>
<td>12.04</td>
<td>2</td>
<td>-11.99</td>
<td>0.25</td>
<td>6.89</td>
<td>0.45</td>
<td>30</td>
<td>73.08</td>
</tr>
<tr>
<td>110</td>
<td>0.362</td>
<td>39.8</td>
<td>12.04</td>
<td>2</td>
<td>-11.99</td>
<td>0.25</td>
<td>6.89</td>
<td>0.45</td>
<td>30</td>
<td>74.92</td>
</tr>
<tr>
<td>150</td>
<td>0.261</td>
<td>39.2</td>
<td>12.04</td>
<td>2</td>
<td>-12</td>
<td>0.25</td>
<td>6.89</td>
<td>0.45</td>
<td>30</td>
<td>76.21</td>
</tr>
<tr>
<td>220</td>
<td>0.175</td>
<td>38.5</td>
<td>12.04</td>
<td>2</td>
<td>-11.99</td>
<td>0.25</td>
<td>6.89</td>
<td>0.45</td>
<td>30</td>
<td>77.28</td>
</tr>
<tr>
<td>250</td>
<td>0.154</td>
<td>38.5</td>
<td>12.04</td>
<td>2</td>
<td>-11.98</td>
<td>0.25</td>
<td>6.89</td>
<td>0.45</td>
<td>30</td>
<td>77.48</td>
</tr>
</tbody>
</table>

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

Table 8. Line Regulation AC Supply

<table>
<thead>
<tr>
<th>V_{in}, V AC</th>
<th>P_{in}, W</th>
<th>V_{01}, V AC</th>
<th>I_{01}, A</th>
<th>V_{02}, V AC</th>
<th>I_{02}, A</th>
<th>V_{03}, V AC</th>
<th>I_{03}, A</th>
<th>P_{out}, W</th>
<th>EFFICIENCY</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>42.33</td>
<td>12.04</td>
<td>2</td>
<td>-11.96</td>
<td>0.25</td>
<td>6.88</td>
<td>0.45</td>
<td>30</td>
<td>70.45</td>
</tr>
<tr>
<td>110</td>
<td>40.91</td>
<td>12.04</td>
<td>2</td>
<td>-11.98</td>
<td>0.25</td>
<td>6.88</td>
<td>0.45</td>
<td>30</td>
<td>72.91</td>
</tr>
<tr>
<td>220</td>
<td>39.22</td>
<td>12.04</td>
<td>2</td>
<td>-11.99</td>
<td>0.25</td>
<td>6.88</td>
<td>0.45</td>
<td>30</td>
<td>76.06</td>
</tr>
<tr>
<td>250</td>
<td>38.37</td>
<td>12.04</td>
<td>2</td>
<td>-11.98</td>
<td>0.25</td>
<td>6.89</td>
<td>0.45</td>
<td>30</td>
<td>77.75</td>
</tr>
<tr>
<td>276</td>
<td>38</td>
<td>12.04</td>
<td>2</td>
<td>-11.98</td>
<td>0.25</td>
<td>6.89</td>
<td>0.45</td>
<td>30</td>
<td>78.5</td>
</tr>
</tbody>
</table>

Figure 9. Output Rail (V) versus AC Input Voltage (V)
6.3 **Load Regulation**

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

<table>
<thead>
<tr>
<th>% LOAD</th>
<th>( I_{\text{P}, \text{A}} ) RATED</th>
<th>( I_{\text{P}, \text{A}} ) ACTUAL</th>
<th>( V_{\text{IN}, +12 , \text{V}} )</th>
<th>( I_{\text{IN}, -12 , \text{V}} ) RATED</th>
<th>( I_{\text{IN}, -12 , \text{V}} ) ACTUAL</th>
<th>( V_{\text{IN}, -12 , \text{V}} )</th>
<th>( I_{\text{OUT}, \text{A}} ) RATED</th>
<th>( I_{\text{OUT}, \text{A}} ) ACTUAL</th>
<th>( V_{\text{OUT}, +6.75 , \text{V}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>100%</td>
<td>2</td>
<td>2</td>
<td>12.03</td>
<td>0.25</td>
<td>0.25</td>
<td>–11.97</td>
<td>0.45</td>
<td>0.45</td>
<td>6.88</td>
</tr>
<tr>
<td>80%</td>
<td>2</td>
<td>1.6</td>
<td>12.05</td>
<td>0.25</td>
<td>0.2</td>
<td>–11.96</td>
<td>0.45</td>
<td>0.36</td>
<td>6.89</td>
</tr>
<tr>
<td>60%</td>
<td>2</td>
<td>1.2</td>
<td>12.06</td>
<td>0.25</td>
<td>0.15</td>
<td>–11.95</td>
<td>0.45</td>
<td>0.27</td>
<td>6.91</td>
</tr>
<tr>
<td>40%</td>
<td>2</td>
<td>0.8</td>
<td>12.08</td>
<td>0.25</td>
<td>0.1</td>
<td>–11.94</td>
<td>0.45</td>
<td>0.18</td>
<td>6.93</td>
</tr>
<tr>
<td>20%</td>
<td>2</td>
<td>0.4</td>
<td>12.09</td>
<td>0.25</td>
<td>0.05</td>
<td>–11.93</td>
<td>0.45</td>
<td>0.09</td>
<td>6.87</td>
</tr>
<tr>
<td>10%</td>
<td>2</td>
<td>0.2</td>
<td>12.1</td>
<td>0.25</td>
<td>0.025</td>
<td>–11.92</td>
<td>0.45</td>
<td>0.045</td>
<td>6.87</td>
</tr>
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</table>
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

<table>
<thead>
<tr>
<th>Variation in ( V_{01} ) load at 24 V DC</th>
<th>( I_{01}, A )</th>
<th>( V_{01} + 12 \text{ V} )</th>
<th>% REGULATION</th>
<th>( V_{02} - 12 \text{ V} )</th>
<th>% REGULATION</th>
<th>( V_{03} + 6.75 \text{ V} )</th>
<th>% REGULATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>12.03</td>
<td>&lt; 1%</td>
<td>−11.98</td>
<td>&lt; 1%</td>
<td>6.88</td>
<td>&lt; 4%</td>
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<tr>
<td>1.75</td>
<td>12.04</td>
<td>−11.94</td>
<td>6.85</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td>12.05</td>
<td>−11.93</td>
<td>6.82</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.25</td>
<td>12.06</td>
<td>−11.94</td>
<td>6.79</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>12.07</td>
<td>−11.98</td>
<td>6.77</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.75</td>
<td>12.08</td>
<td>−11.93</td>
<td>6.72</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>12.09</td>
<td>−11.92</td>
<td>6.64</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Variation in ( V_{02} ) load at 24 V DC</th>
<th>( I_{02}, A )</th>
<th>( V_{01} + 12 \text{ V} )</th>
<th>% REGULATION</th>
<th>( V_{02} - 12 \text{ V} )</th>
<th>% REGULATION</th>
<th>( V_{03} + 6.75 \text{ V} )</th>
<th>% REGULATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25</td>
<td>12.03</td>
<td>&lt; 1%</td>
<td>−11.99</td>
<td>&lt; 2%</td>
<td>6.89</td>
<td>&lt; 1%</td>
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<tr>
<td>0.225</td>
<td>12.04</td>
<td>−11.88</td>
<td>6.88</td>
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<td></td>
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<td>0.2</td>
<td>12.04</td>
<td>−11.86</td>
<td>6.89</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>0.175</td>
<td>12.04</td>
<td>−11.95</td>
<td>6.89</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.15</td>
<td>12.04</td>
<td>−12.06</td>
<td>6.89</td>
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<td>0.125</td>
<td>12.04</td>
<td>−12.18</td>
<td>6.89</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.1</td>
<td>12.04</td>
<td>−12.18</td>
<td>6.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.075</td>
<td>12.04</td>
<td>−12.18</td>
<td>6.9</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.05</td>
<td>12.04</td>
<td>−12.19</td>
<td>6.9</td>
<td></td>
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<td></td>
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</table>
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: $V_{\text{BOOST}}$, CH2: Booster FET Drain 24-V DC

Figure 16. CH1: $V_{\text{BOOST}}$, 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.

---

**Figure 32. Average Test Result at 230-V AC**
6.6 **EMC**

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

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

6.7 **Summary of Results**
Table 12. Summary of Results

<table>
<thead>
<tr>
<th>TEST</th>
<th>PARAMETER</th>
<th>TEST RESULT (OBSERVATION)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line Regulation</td>
<td>20 to 250-V DC</td>
<td>&lt; 1%</td>
</tr>
<tr>
<td></td>
<td>80 to 276-V AC</td>
<td>&lt; 1%</td>
</tr>
<tr>
<td>Efficiency</td>
<td>20 to 250-V DC</td>
<td>Up to 63 to 77% at full load</td>
</tr>
<tr>
<td></td>
<td>80 to 276-V AC</td>
<td>Up to 70 to 78% at full load</td>
</tr>
<tr>
<td>Load Regulation</td>
<td>10 to 100% load variation</td>
<td>&lt; 1%</td>
</tr>
<tr>
<td></td>
<td>Cross Load Regulation for V01</td>
<td>±12 V &lt; 1% 6.75 V &lt; 4%</td>
</tr>
<tr>
<td></td>
<td>Cross Load Regulation for V02</td>
<td>±12 V &lt; 1% 6.75 V &lt; 4%</td>
</tr>
<tr>
<td>Ripple</td>
<td></td>
<td>&lt; 200 mV pk-pk for ±12 V</td>
</tr>
<tr>
<td>Ride through Performance</td>
<td>Dip in the output rails &lt; 5% for time</td>
<td>&gt; 100 ms</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>DESIGNATOR</th>
<th>QUANTITY</th>
<th>DESCRIPTION</th>
<th>PACKAGE REFERENCE</th>
<th>PART NUMBER</th>
<th>MANUFACTURER</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCB1</td>
<td>1</td>
<td>Printed Circuit Board</td>
<td></td>
<td>TIDA-00127</td>
<td>Any</td>
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<tr>
<td>B1, B2, B3, B4, B5, B6</td>
<td>6</td>
<td>FERRITE CHIP 70 OHM 4000MA 0603</td>
<td>C61P7000AC</td>
<td>Samsung</td>
<td></td>
</tr>
<tr>
<td>C1, C2, C3, C21</td>
<td>4</td>
<td>CAP FILM 0.47UF 560VDC RADIAL</td>
<td>R4K6347050F1M</td>
<td>Kemet</td>
<td></td>
</tr>
<tr>
<td>C3, C42</td>
<td>2</td>
<td>CAP CER 100PF 1KV 10% RADIAL</td>
<td>DB6833A10KFX2A</td>
<td>Mufuta</td>
<td></td>
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<tr>
<td>C4</td>
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<td>CAP ALUM 33UF 450V 20% RADIAL</td>
<td>UCS2W30MH6</td>
<td>Nichicon</td>
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<tr>
<td>C6</td>
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<td>CAP ALUM 68UF 450V 20% RADIAL</td>
<td>EKX0451EL680MVNS</td>
<td>United Chemicon</td>
<td></td>
</tr>
<tr>
<td>C7, C8</td>
<td>2</td>
<td>CAP CER 330PF 300VAC 10% RADIAL</td>
<td>VY2331K29Y5S63V7</td>
<td>Vishay</td>
<td></td>
</tr>
<tr>
<td>C9, C10, C19, C26</td>
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<td>CAP CER 2200PF 300VAC 20% RADIAL</td>
<td>VY2222MS5Y5S63V7</td>
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<tr>
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<td>Vishay</td>
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<tr>
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<td>CAP ALUM 33UF 35V 20% RADIAL</td>
<td>35YJ33M3X11</td>
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<tr>
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<td>CAP CER 470PF 50V 5% NPO 0603</td>
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<tr>
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<td>C2012X5R1C226K125AC</td>
<td>TDK</td>
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<tr>
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<td>Kemet</td>
<td></td>
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<tr>
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<tr>
<td>D1</td>
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<td>Diode, Ultrafast, Power Rectifier, 600V, 4A</td>
<td>MUR460RLG</td>
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<td>MCC</td>
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<td>P6KE120A</td>
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<td>1N4907</td>
<td>Fairchild</td>
<td></td>
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<tr>
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<tr>
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</tr>
<tr>
<td>F1</td>
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<td>FUSE SLOW 250VAC 5A RADIAL</td>
<td>RST 5</td>
<td>BEL</td>
<td></td>
</tr>
<tr>
<td>FID1, FID2, FID3, FID4, FID5, FID6</td>
<td>6</td>
<td>Fiducial mark. There is nothing to buy or mount.</td>
<td>N/A</td>
<td>N/A</td>
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</tr>
<tr>
<td>H1, H2, H3, H4</td>
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<td>Mounting Hole M3 3.5mm Screw</td>
<td>STD</td>
<td>STD</td>
<td></td>
</tr>
<tr>
<td>HT1, HT2</td>
<td>2</td>
<td>Heatsink, TO-220</td>
<td>1.181 x 2.402 inch</td>
<td>CHT-2-38E</td>
<td>Ohmite</td>
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<tr>
<td>J1, J2</td>
<td>2</td>
<td>Terminal Block, 2x1, 5.08mm, TH</td>
<td>OST7CC02162</td>
<td>On-Shore Technology</td>
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<tr>
<td>J3</td>
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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 38. Top Layer

Figure 39. Bottom Layer
Figure 40. Bottom Solder Mask

Figure 41. Bottom Overlay
Figure 42. Drill Pattern

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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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