Design Guide: TIDA-010071
SAE J1772-Compliant Electric Vehicle Service Equipment Reference Design for Level 1 and 2 EV Charger

Description
Electric vehicle service equipment (EVSE) facilitates power delivery to electric vehicles safely from the grid. An EVSE control system consists of an auxiliary power stage, an off-board AC/DC high power stage (only in DC charging stations), energy metering unit, AC and DC residual current detector, an isolation monitor unit, relays and contactors with drive, two-way communication over single wire, and service and user interfaces. This reference design highlights an ultra-low standby isolated AC/DC auxiliary power stage followed by converters and linear regulators, a comparator-based control pilot interface to meet the SAE J1772 standard, an efficient relay and contactor drive, and isolated line voltage sensing across the relay and contactor.

Resources
- TIDA-010071 Design Folder
- UCC28740 Product Folder
- TLV1805 Product Folder
- DRV110 Product Folder
- ISO1212 Product Folder
- TL431LI, LP2951, LM79L Product Folder
- TPS715A, TPS7A30 Product Folder
- TPS561201, TPS62172 Product Folder

Features
- Ultra-low standby UCC28740-based isolated AC/DC stage to achieve ENERGY STAR® certification for EV charging stations
- Tight output voltage regulation (< ±5%) of LDOs and the high slew rate of the TLV1805 device ensures SAE J1772 certification for the control pilot interface
- Ultra-low standby as well as cost-optimized converters and linear regulators to power up points-of-load
- DRV110 current controller to drive high-current relays and contactors for thermal protection and reducing power dissipation
- Isolated line voltage sensing using the ISO1212 digital-input receiver for welded relay and contactor detection

Applications
- AC charging (pile) station

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1 System Description

Electric vehicles (EVs), including plug-in hybrid electric vehicles (PHEVs), receive energy from the electrical grid through electric vehicle supply equipment (EVSE), more commonly known as EV chargers. To facilitate the power delivery to the vehicle, the EVSE sits between a stable grid connection and the vehicle, as Figure 1 shows.

Figure 1. AC Level 1 and Level 2 System Configuration
The primary EVSE functionality includes:

- **Regulated electrical current:** Ensures that the optimal current is provided and falls within the maximum current the EV can handle.
- AC/DC residual current detection (RCD)
- Relay and contactor drive and latched contact detection
- Energy metering
- **Automatic disconnect:** When a hardware fault is detected, the power is shut off, to avoid risks like battery damage, an electrical short or a fire.
- **Safety lock-out feature:** Prevents current from flowing when the charger is not connected to an EV.

An EVSE control system mainly consists of auxiliary power stage, off-board AC/DC high power stage (only in DC charging stations), energy metering, AC and DC residual current detection, isolation monitor unit, relays and contactors with drive, two-way communication, and service and user interfaces. The EVSE design for EV charging stations can present several challenges such as:

**SAE J1772 or equivalent standard compliant EV charging stations:**

Many electric vehicle manufacturers have adopted the SAE J1772 standard for electrical connections to an EV. The same specifications also translate into international localizations, with differing form factors. The control pilot is the primary control conductor and is connected to the equipment ground through control circuitry on the vehicle and performs the following functions:

- Verifies that the vehicle is present and connected
- Permits energization and de-energization of the supply
- Transmits supply equipment current rating to the vehicle
- Monitors the presence of the equipment ground
- Establishes vehicle ventilation requirements
Table 1 shows the SAE J1772 standard mandates control pilot circuit generator parameters:

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>MIN</th>
<th>NOM</th>
<th>MAX</th>
<th>UNITS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage high, open circuit</td>
<td>11.40</td>
<td>12.00</td>
<td>12.60</td>
<td>V</td>
</tr>
<tr>
<td>Voltage low, open circuit</td>
<td>−11.40</td>
<td>−12.00</td>
<td>−12.60</td>
<td>V</td>
</tr>
<tr>
<td>Frequency</td>
<td>1000</td>
<td></td>
<td></td>
<td>Hz</td>
</tr>
<tr>
<td>Pulse width (5)</td>
<td>5</td>
<td></td>
<td></td>
<td>µs</td>
</tr>
<tr>
<td>Rise time (3)</td>
<td>2</td>
<td></td>
<td></td>
<td>µs</td>
</tr>
<tr>
<td>Fall time (3)</td>
<td>2</td>
<td></td>
<td></td>
<td>µs</td>
</tr>
<tr>
<td>Settling time (4)</td>
<td>3</td>
<td></td>
<td></td>
<td>µs</td>
</tr>
</tbody>
</table>

(1) Tolerances to be maintained over the environmental conditions and useful life as specified by the manufacturer
(2) Measured at 50% points of complete negative-to-positive or positive-to-negative transitions
(3) 10% to 90% of complete negative-to-positive transition or 90% to 10% of complete positive-to-negative transition measured between the pulse generator output and R1. Note that the term generator is referring to the EVSE circuitry prior to and driving the 1-Ω source resistor with a ±12-V square wave. This circuitry shall have rise/fall times faster than 2 µs. Rise and fall times slower than this will begin to add noticeably to the output rise and fall times dictated by the 1-Ω resistor and all capacitance on the pilot line.
(4) To 95% of steady-state value, measured from the start of transition.

AC and DC leakage, residual current detection (RCD):
The primary requirement in providing protection during EV charging is the ability to detect AC and DC residual currents and thereby mitigate the risk of electric shock or fire.

Low standby EVSE for ENERGY STAR® certification:
As most of the EV chargers are typically in a standby mode for about 85% of the lifetime of the product, consumers and businesses can save additional money by choosing an ENERGY STAR certified EV charger, which on average use 40% less energy than a standard EV charger when the charger is in standby mode (that is, not actively charging a vehicle).

Efficient relay and contactor drive:
In normal use cases, high-current relays or contactors can typically draw 10s to 100s of milliamps as an inductive load, requiring specific drive architectures. Because of the amount of time that a relay or contactor requires to remain powered, an efficient drive solution is preferred to avoid thermal problems.

Contact weld detection:
For safety reasons, detecting the output voltage of the relay and contactor is critical. The contacts can experience arcing and become fused together, providing power to the plug even when the system is not powering it. Checking that the operation completed correctly is important and should be done every time the relay is opened.

This reference design showcases ultra-low standby isolated AC/DC auxiliary power stage followed by ultra-low Iq as well as cost-optimized converters and linear regulators, comparator-based control pilot interface to meet SAE J1772 standard, efficient relay and contactor driver solution and digital isolator based line voltage sensing to detect fusing of relay and contactor contacts due to arcing.
### 1.1 Key System Specifications

#### Table 2. Key System Specifications

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>NOTES AND CONDITIONS</th>
<th>MIN</th>
<th>NOM</th>
<th>MAX</th>
<th>UNIT</th>
<th>DETAILS</th>
</tr>
</thead>
<tbody>
<tr>
<td>INPUT CHARACTERISTICS</td>
<td>Input voltage, $V_{IN}$</td>
<td>85</td>
<td>120/230</td>
<td>265</td>
<td>V</td>
<td>$V_{RMS}$ Line voltage</td>
</tr>
<tr>
<td></td>
<td>Line frequency, $f_{LINE}$</td>
<td>47</td>
<td>60/50</td>
<td>63</td>
<td>Hz</td>
<td></td>
</tr>
<tr>
<td>OUTPUT CHARACTERISTICS</td>
<td>Output voltage, $V_{OUT1}$, Flyback output 1</td>
<td>13</td>
<td>V</td>
<td>UCC28740-based AC/DC flyback power stage with 3 output</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Output current, $I_{OUT1}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Output voltage, $V_{OUT2}$, Flyback output 2</td>
<td>−13.5</td>
<td>−22</td>
<td>V</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Output current, $I_{OUT2}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Output voltage, $V_{OUT3}$, Flyback output 3</td>
<td>7.5</td>
<td>12</td>
<td>V</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Output current, $I_{OUT3}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total output power, $P_{OUT}$, Output power of flyback power stage</td>
<td>15</td>
<td>W</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>POINT OF LOAD CHARACTERISTICS</td>
<td>Control pilot signal generator high voltage</td>
<td>+12</td>
<td>V</td>
<td>TLV760 or TPS715A used to power TLV1805</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Control pilot signal generator low voltage</td>
<td>−12</td>
<td>V</td>
<td>TPS7A30 used to power TLV1805</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Relay drive voltage</td>
<td>+13</td>
<td>V</td>
<td>Output 1 of flyback power stage</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Leakage current sensor high voltage</td>
<td>+5</td>
<td>V</td>
<td>LP2951 or TLV704 used to power leakage sensor</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Leakage current sensor low voltage</td>
<td>−5</td>
<td>V</td>
<td>TPS7A30 or LM79L used to power leakage sensor</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>I/O voltage</td>
<td>+3.3</td>
<td>V</td>
<td>TPS561201 or TPS62172 used to generate 3.3-V rail</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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2 System Overview

2.1 Block Diagram

Figure 2. TIDA-010071 Block Diagram
2.2 Design Considerations

2.2.1 Isolated AC/DC Power Supply Design

The isolated AC/DC power stage is multiple outputs winding flyback stage based on the UCC28740 device. The UCC28740 controller provides Constant-Voltage (CV) using an optical coupler to improve transient response to large-load steps. Constant-Current (CC) regulation is accomplished through Primary-Side Regulation (PSR) techniques. This device processes information from the optocoupled feedback and an auxiliary flyback winding for precise high-performance control of the output voltage and current. A Q1-rated variant of the UCC28740-Q1 device exists, if automotive qualification is required.

Table 3. Design Parameters

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>NOTES AND CONDITIONS</th>
<th>MIN</th>
<th>NOM</th>
<th>MAX</th>
<th>UNIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>INPUT CHARACTERISTICS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Input voltage, ( V_{IN} )</td>
<td></td>
<td>85</td>
<td>115/230</td>
<td>265</td>
<td>( V_{RMS} )</td>
</tr>
<tr>
<td>Maximum input current ( V_{IN} - V_{IN(min)} ) ( I_{OUT} = I_{OUT(max)} )</td>
<td>0.265</td>
<td>( A_{RMS} )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Line frequency</td>
<td></td>
<td>47</td>
<td>60/50</td>
<td>63</td>
<td>Hz</td>
</tr>
<tr>
<td>Desired capacitor bulk voltage, ( V_{BULK(desired)} )</td>
<td>80</td>
<td>V</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No load input power consumption ( V_{IN(min)} ) ( V_{IN} ) ( \leq ) ( V_{IN(max)} ) ( I_{OUT} = 0 A )</td>
<td>20</td>
<td>mW</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OUTPUT CHARACTERISTICS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Output voltage, ( V_{OUT1} ) ( V_{IN(min)} ) ( V_{IN} ) ( \leq ) ( V_{IN(max)} )</td>
<td>13</td>
<td>V</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Output current, ( I_{OUT1} )</td>
<td></td>
<td>0.5</td>
<td>A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Output voltage, ( V_{OUT2} ) ( V_{IN(min)} ) ( V_{IN} ) ( \leq ) ( V_{IN(max)} )</td>
<td>-13.5</td>
<td>-22</td>
<td>V</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Output current, ( I_{OUT2} )</td>
<td></td>
<td>0.2</td>
<td>A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Output voltage, ( V_{OUT3} ) ( V_{IN(min)} ) ( V_{IN} ) ( \leq ) ( V_{IN(max)} )</td>
<td>7.5</td>
<td>12</td>
<td>V</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Output current, ( I_{OUT3} )</td>
<td></td>
<td>0.3</td>
<td>A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total output power, ( P_{OUT} )</td>
<td></td>
<td>15</td>
<td>W</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Output voltage regulation Line regulation: ( V_{IN(min)} ) ( V_{IN} ) ( \leq ) ( V_{IN(max)} ), ( I_{OUT} ) ( \leq ) ( I_{OUT(max)} )</td>
<td>0.1%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Load regulation: ( 0 A ) ( \leq ) ( I_{OUT} ) ( \leq ) ( I_{OUT(max)} )</td>
<td>0.1%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Output voltage ripple ( V_{IN(min)} ) ( V_{IN} ) ( \leq ) ( V_{IN(max)} ), ( 0 A ) ( \leq ) ( I_{OUT} ) ( \leq ) ( I_{OUT(max)} )</td>
<td>100</td>
<td>mVpp</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total output overcurrent, ( I_{OCC} )</td>
<td>( V_{IN(min)} ) ( V_{IN} ) ( \leq ) ( V_{IN(max)} )</td>
<td>1.1</td>
<td>A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum output voltage, CC mode ( V_{IN(min)} ) ( V_{IN} ) ( \leq ) ( V_{IN(max)} ), ( I_{OUT} ) ( \leq ) ( I_{OCC} )</td>
<td>1.78</td>
<td>2</td>
<td>V</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brown-out protection ( I_{OUT} ) ( \leq ) ( I_{OUT(max)} ) to 0-A load transient</td>
<td>68</td>
<td>( V_{RMS} )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transient response undershoot ( I_{OUT} ) ( \leq ) ( I_{OUT(max)} ) to 0-A load transient</td>
<td>0.05</td>
<td>V</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transient response time ( I_{OUT} ) ( \leq ) ( I_{OUT(max)} ) to 0-A load transient</td>
<td>20</td>
<td>ms</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SYSTEMS CHARACTERISTICS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Switching frequency, ( f_{SW} )</td>
<td></td>
<td>1.2</td>
<td>80</td>
<td>kHz</td>
<td></td>
</tr>
<tr>
<td>Average efficiency</td>
<td>25%, 50%, 75%, 100% load average at Nominal input voltages</td>
<td>80%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operating temperature</td>
<td></td>
<td>25</td>
<td>°C</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
2.2.1.1 Input Bulk Capacitance and Minimum Bulk Voltage

The minimum voltage on the input bulk capacitance is needed to determine the maximum primary-to-secondary turns-ratio of the transformer. The input power of the converter based on target full-load efficiency, the minimum input RMS voltage, and the minimum AC input frequency determine the input capacitance requirement. Maximum input power is determined based on Equation 1:

\[ P_{\text{IN}} = \frac{V_{\text{OCV}} \times I_{\text{OCC}}}{\eta} = \frac{13 \text{ V} \times 0.5 \text{ A} + \left| -15 \text{ V} \right| \times 0.2 \text{ A} + 7 \text{ V} \times 0.3 \text{ A}}{0.8} \approx 14.5 \text{ W} \]

where
- \( V_{\text{OCV}} \) is the regulated output voltage of the converter
- \( I_{\text{OCC}} \) is the converter total output CC target
- \( \eta \) is the converter overall efficiency at full-power output

Equation 2 provides an accurate solution for the total input capacitance based on a target minimum bulk capacitor voltage. Alternatively, to target a given input capacitance value, iterate the minimum capacitor voltage to achieve the target capacitance value.

\[ C_{\text{BULK}} = \frac{2P_{\text{IN}} \times \left\{ 0.25 + \frac{1}{2\pi} \times \arcsin \left( \frac{V_{\text{BULK(desired)}}}{\sqrt{2} \times V_{\text{IN(min)}}} \right) \right\}}{(2V_{\text{IN(min)}}^2 - V_{\text{BULK(desired)}}^2) \times f_{\text{LINE(min)}}} \approx 28 \mu\text{F} \]

Two 18-\( \mu \text{F} \) electrolytic capacitors were used at the input.

2.2.1.2 Transformer Turn-ratio, Primary Inductance, and Primary Peak Current

The target maximum switching frequency at full load, the minimum input-capacitor bulk voltage, and the estimated DCM resonant time determine the maximum primary-to-secondary turns-ratio of the transformer. Initially, determine the maximum-available total duty-cycle of the on-time and secondary conduction time based on the target switching frequency (\( f_{\text{MAX}} \)) and DCM resonant time (\( t_R \)).

At the transition-mode operation limit of DCM, the interval required from the end of the secondary current conduction to the first valley of the \( V_{DS} \) voltage is \( \frac{1}{2} \) of the DCM resonant period (\( t_R \)), or 1 \( \mu \text{s} \) assuming 500-kHz DCM resonant frequency. The maximum allowable MOSFET on-time \( D_{\text{MAX}} \) is determined using Equation 3:

\[ D_{\text{MAX}} = 1 - D_{\text{MAGCC}} - \left( \frac{t_R}{2} \times f_{\text{MAX}} \right) = 1 - 0.425 - 80 \text{ kHz} \times \frac{2 \mu\text{s}}{2} = 0.495 \]

where
- \( t_R \) is the estimated period of the LC resonant frequency at the switch node
- \( D_{\text{MAGCC}} \) is defined as the duty cycle of the secondary-diode conduction during CC operation and is fixed internally by the UCC28740 device at 0.425

When \( D_{\text{MAX}} \) is known, the maximum primary-to-secondary turns ratio is determined with Equation 4. The total voltage on the secondary winding must be determined, which is the sum of \( V_{\text{OCV}} \) and \( V_F \)

\[ N_{\text{PSU(max)}} = \frac{D_{\text{MAX}} \times V_{\text{BULK(min)}}}{D_{\text{MAGCC}} \times (V_{\text{OCV}} + V_F)} \]

Assuming \( V_F = 0.6 \text{ V} \):

\[ N_{\text{PSU(max)}} = \frac{0.495 \times 80}{0.425 \times (13 + 0.6)} = 6.85 \]

A higher turns-ratio generally improves efficiency, but may limit operation at a low input voltage. Transformer design iterations are generally necessary to evaluate system-level performance trade-offs.
The primary transformer inductance is calculated using the standard energy storage equation for flyback transformers. The primary current, maximum switching frequency, output voltage and current targets, and transformer power losses are included in Equation 6:

$$L_p = \frac{2 \times (V_{OCV} + V_F + V_{OCBC}) \times I_{OCC}}{\eta_{XFM} \times I_{PP(max)} \times f_{MAX}}$$

The UCC28740 CC regulation is achieved by maintaining $D_{MAGCC}$ at the maximum primary peak current setting. The product of $D_{MAGCC}$ and $V_{CST(max)}$ defines a CC-regulating voltage factor $V_{CCR}$ which is used with $N_{PS}$ to determine the current-sense resistor value necessary to achieve the regulated CC target, $I_{OCC}$ (see Equation 7).

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

$$R_{CS} = \frac{0.33 \times 11}{2 \times 1.1} \times \sqrt{0.9} = 1.56 \Omega$$

where

- $V_{CCR}$ is the CC regulation factor (from the data sheet)
- $V_{CST}$ is the CS-pin current-sense threshold (from the data sheet)

$$I_{PP(max)} = \frac{V_{CST(max)}}{R_{CS}} = 0.81 \frac{A}{1} = 0.81 \text{ A}$$

$$I_{PP(nom)} = \frac{V_{CST(nom)}}{R_{CS}} = 0.773 \frac{A}{1} = 0.773 \text{ A}$$

Two 2-Ω resistors were used in parallel for current sense and the primary inductance of the selected transformer is 680-µH.

$N_{AS}$ is determined by the lowest target operating output voltage while in CC regulation and by the $V_{DD}$ UVLO turnoff threshold of the UCC28740 device. Additional energy is supplied to $V_{DD}$ from the transformer leakage-inductance which allows a lower turns ratio to be used in many designs.

$$N_{AS} = \frac{V_{DD(off)} + V_{FA}}{V_{OCC} + V_F} = \frac{8.15 + 0.6}{13.5 + 0.6} = 0.62$$

where

- $V_{DD(off)}$ is UCC28740 turnoff threshold (from the data sheet)
- $V_{OCC}$ is the lowest output voltage target of the converter while in constant-current regulation
- $V_{FA}$ is voltage drop across rectifier diode on auxiliary side of flyback stage

2.2.1.3 Transformer Parameter Calculations: Primary and Secondary RMS Currents

With the primary inductance of 680 µH, the absolute maximum switching frequency is calculated from Equation 11:

$$f_{MAX} = \frac{2 \times (13 + 0.6) \times 1.1}{0.9 \times 0.81^2 \times 680 \mu \text{H}} = 74.5 \text{ kHz}$$

The maximum switching period is:

$$t_{SW} = \frac{1}{f_{MAX}} = \frac{1}{74.5 \text{ kHz}} = 13.4 \mu \text{s}$$
The actual maximum on-time is given by Equation 13:

\[ t_{\text{ON(max)}} = \frac{I_{\text{PP(nom)}} \times L_P}{V_{\text{BULK(min)}}} = \frac{0.773 \times 680 \, \mu\text{H}}{80} = 6.5 \, \mu\text{s} \]  

The maximum duty cycle of operation (D_{\text{MAX}}) is:

\[ D_{\text{MAX}} = \frac{t_{\text{ON(max)}}}{t_{\text{SW}}} = \frac{6.5 \, \mu\text{s}}{13.4 \, \mu\text{s}} = 0.485 \]  

The transformer primary RMS current (I_{\text{PRMS}}) is:

\[ I_{\text{PRMS}} = I_{\text{PP(nom)}} \frac{D_{\text{MAX}}}{3} = 0.773 \times \sqrt{\frac{0.485}{3}} = 0.310 \, \text{A} \]  

The transformer secondary peak current RMS current (I_{\text{SEC(max)}}) is:

\[ I_{\text{SEC(max)}} = I_{\text{PP(max)}} \times N_{\text{PS}} = 0.81 \times 11 = 8.91 \, \text{A} \]  

\[ I_{\text{SEC(max)}} = I_{\text{PP(max)}} \times N_{\text{PS}} = 0.81 \times 11 = 8.91 \, \text{A} \]  

The transformer secondary RMS current (I_{\text{SEC_RMS}}) is:

\[ I_{\text{SEC_RMS}} = I_{\text{SEC(max)}} \frac{D_{\text{MAX}}}{3} = 8.91 \times \frac{0.485}{3} = 3.58 \, \text{A} \]  

Based on these calculations, a Würth Elektronik™ transformer was designed for this application (part number 750318383), which has the following specifications:

- N_{\text{PS}} = 11 ±2%
- N_{\text{PA}} = 9.78 ±2%
- L_P = 680 ±10% \, \mu\text{H}
- L_{\text{LK}} = 10 \, \mu\text{H} (which denotes the primary leakage inductance)

2.2.1.4 **Main Switching Power MOSFET Selection**

The drain-to-source RMS current, I_{\text{DS_RMS}}, through switching FET is calculated using Equation 18:

\[ I_{\text{DS_RMS}} = I_{\text{PP(max)}} \frac{D_{\text{MAX}}}{3} = 0.81 \times \sqrt{\frac{0.485}{3}} = 0.325 \, \text{A} \]  

Select a MOSFET with five times the I_{\text{DS_RMS}} calculated. The maximum voltage across the FET can be estimated using Equation 19:

\[ V_{\text{DSPK}} = \left( V_{\text{IN(max)}} \times \sqrt{2} \right) + \left( V_{\text{OCV}} + V_F \right) \times N_{\text{PS}} + V_{\text{LK}} = \left( 265 \times \sqrt{2} \right) + \left( 13 + 0.6 \right) \times 11 + 150 = 624.31 \, \text{V} \]  

Considering a de-rating of 15% and leakage spike of around 150 V, the voltage rating of the MOSFET must be around 700-V DC.

2.2.1.5 **Rectifying Diode Selection**

Calculate the secondary output diode or synchronous rectifier FET reverse voltage or blocking voltage needed (V_{\text{DIODE_BLOCKING}}):

\[ V_{\text{DIODE_BLOCKING}} = \frac{V_{\text{IN_DC(max)}}}{N_{\text{PS}}} + V_{\text{OCV}} + V_{\text{OCBC}} = \frac{375}{11} + 13 = 47.1 \, \text{V} \]  

For this reference design, the Schottky diode with 60-V voltage and 1-A forward current rating is selected.
2.2.1.6 Output Capacitor Selection

For this reference design, the output capacitor ($C_{OUT}$) for output is selected to prevent $V_{OUT} (= 13 \text{ V})$ from dropping below the minimum output voltage ($V_{OTRM}$) during transients up to 0.1 V and ripple voltage less than 100 mV.

$$C_{OUT} \geq \frac{I_{OCC} \times (t)}{2 \times (V_{OCV} - V_{OTRM})}$$

Assuming $V_{OTRM} = 12.9 \text{ V}$,

$$C_{OUT} \geq \frac{1.1 \times (50 \mu\text{s})}{13 - 12.9} \geq 275 \mu\text{F}$$

Considering the allowable output ripple voltage of 100 mV (5%), the ESR and RMS current of the capacitor must be:

$$ESR = \frac{V_{OUT,RIPPLE}}{I_{SEC(max)}} = 100 \text{ mV} \quad 8.91 \text{ A} = 11.22 \text{ m\Omega}$$

$$I^{COUT,RMS} = \sqrt{(I^{SEC,RMS})^2 - (I^{OCC})^2} = \sqrt{(3.58)^2 - (1.1)^2} = 3.4 \text{ A}$$

One 680-µF capacitor was selected at the output.

2.2.1.7 Capacitance on VDD Pin

The capacitance on VDD needs to supply the device operating current until the output of the converter reaches the target minimum operating voltage in CC regulation. The capacitance on VDD must supply the primary-side operating current used during startup and between low-frequency switching pulses. The largest result of two independent calculations denoted in Equation 25 determines the value of $C_{VDD}$.

At start-up, when $V_{VDD(on)}$ is reached, $C_{VDD}$ alone supplies the device operating current and MOSFET gate current until the output of the converter reaches the target minimum operating voltage in CC regulation, $V_{OCC}$. Now the auxiliary winding sustains VDD for the UCC28740 device above UVLO. The total output current available to the load and to charge the output capacitors is the CC-regulation target, $I_{OCC}$.

Equation 25 assumes that all of the output current of the converter is available to charge the output capacitance until $V_{OCC}$ is achieved. For typical applications, Equation 26 includes an estimated $q \times f_{SW(max)}$ of average gate drive current and a 1-V margin added to $V_{VDD}$.

$$C_{VDD} \geq \frac{(I_{RUN} + q \times f_{SW(max)}) \times C_{OUT} \times V_{OCC}}{I_{OCC} \times V_{DD(on)} - (V_{DD(on)} + 1 \text{ V})}$$

$$C_{VDD} \geq \frac{(2 \text{ mA} + 9.9 \text{ nC} \times 80 \text{ kHz}) \times 680 \mu\text{F} \times 13.5}{21 - (8.5 + 1 \text{ V})} \geq 1.85 \mu\text{F}$$

The current design uses 10-µF and 2.2-µF capacitors.
### 2.2.1.8 Open-loop Voltage Regulation Versus Pin Resistor Divider, Line Compensation Resistor

The resistor divider at the VS pin determines the output voltage regulation point of the flyback converter. Also, the high-side divider resistor ($R_{S1}$) determines the line voltage at which the controller enables continuous DRV operation. $R_{S1}$ is initially determined based on transformer auxiliary-to-primary turns ratio and desired input voltage operating threshold.

$$R_{S1} = \frac{V_{IN(run)} \times \sqrt{2}}{N_{PA} \times I_{VL(min)}}$$

where
- $N_{PA}$ is the transformer primary-to-auxiliary turns ratio
- $V_{IN(run)}$ is the AC RMS voltage to enable turn on of the controller (run); in case of DC input, leave out the $\sqrt{2}$ term in the equation
- $V_{SL(min)}$ is the run threshold for the current pulled out of the VS pin during the switch time (see the Electrical Characteristics section of the UCC28740 data sheet)

$$R_{S1} = \frac{80 \times \sqrt{2}}{9.78 \times 275 \, \mu A} = 42.05 \, k\Omega$$

The low-side VS pin resistor is selected based on the desired $V_{OUT}$ regulation voltage in open-loop conditions and sets the maximum allowable voltage during open-loop conditions.

$$R_{S2} = \frac{R_{S1} \times V_{OVPTH}}{N_{AS} \times (V_{OV} - V_{F}) - V_{OVPTH}}$$

where
- $V_{OV}$ is the maximum allowable peak voltage at the converter output
- $V_{F}$ is the output-rectifier forward drop at near-zero current
- $N_{AS}$ is the transformer auxiliary-to-secondary turns ratio
- $V_{OVPTH}$ is the overvoltage detection threshold at the VS input (see the Electrical Characteristics section of the UCC28740 data sheet)

$$R_{S2} = \frac{42.05 \, k\Omega \times 4.6}{1.12 \times (13.5 - 0.6) - 4.6} = 20.8 \, k\Omega$$

The UCC28740 device maintains tight CC regulation over varying input lines by using the line-compensation feature. The line-compensation resistor ($R_{LC}$) value is determined by the current flowing in $R_{S1}$ and the total internal gate drive and external MOSFET turnoff delay. Assuming an internal delay of 50 ns in the UCC28740 device:

$$R_{LC} = \frac{K_{LC} \times R_{S1} \times R_{CS} \times t_{D} \times N_{PA}}{L_{P}}$$

$$R_{LC} = \frac{28.6 \times 42.05 \, k\Omega \times 1 \times (46 \, ns + 50 \, ns) \times 9.78}{680 \, \mu \text{H}} = 1.6 \, k\Omega$$

where
- $t_{D}$ is the current-sense delay including MOSFET turnoff delay
- $K_{LC}$ is a current-scaling constant (see the Electrical Characteristics section of the UCC28740 data sheet)
2.2.1.9 Feedback Elements

The output voltage is set through the sense network resistors $R_{FB1}$ and $R_{FB2}$. Select the value of the feedback resistor based on the desired output voltage with Equation 32:

$$V_{in} = \frac{V_{OCV} \times R_{FB2}}{R_{FB1} + R_{FB2}}$$

where

- $V_{in} = 2.5 \text{ V}$

The op amp compensation network, $Z_{FB}$, is determined using well-established design techniques for control-loop stability. Typically, a type-II compensation network is used.

2.2.2 Non-isolated Power Supply for Point-of-loads

Many different supply rails need to be generated to derive I/O voltage, bipolar power rail for control pilot signal interface, and analog voltage for the peripherals. The outputs of the UCC28740-based isolated AC/DC stage is used to derive power for the required peripherals. This reference design highlights low cost as well as low standby point of load devices as Table 4 shows:

<table>
<thead>
<tr>
<th>DC/DC VOLTAGE CONVERSION</th>
<th>SELECTED COST OPTIMIZED DEVICES</th>
<th>SELECTED LOW STANDBY DEVICES</th>
<th>POWERED PERIPHERAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>13 V to 12 V</td>
<td>TLV760</td>
<td>TPS715A</td>
<td>Control pilot signal generator</td>
</tr>
<tr>
<td>13 V to 5 V</td>
<td>LP2951</td>
<td>TLV704</td>
<td>Leakage current sensor, temperature sensor</td>
</tr>
<tr>
<td>13 V to 3.3 V</td>
<td>TPS561201</td>
<td>TPS62172</td>
<td>MCU, memory, user interface LEDs</td>
</tr>
<tr>
<td>−15 V to −12 V</td>
<td>LM79L</td>
<td>TPS7A30</td>
<td>Control pilot signal generator</td>
</tr>
<tr>
<td>−12 V to −5 V</td>
<td>LM79L</td>
<td>TPS7A30</td>
<td>Leakage current sensor</td>
</tr>
</tbody>
</table>

2.2.3 Control Pilot Signal Interface

The control pilot circuit is the primary control means to ensure proper operation when connecting an EV/PHEV to the EVSE. The pilot signal is the key method through which a J1772-compliant EVSE communicates with a vehicle. The pilot signal is based on a 1-kHz, ±12-V PWM signal that is transmitted to a vehicle over the charging chord. The vehicle can then respond by placing various loads on the line, affecting its voltage, which the EVSE measures.

2.2.3.1 J1772 Duty Cycle

The duty cycle of the pilot signals communicate the limit of current the EVSE is capable of supplying to the vehicle; the vehicle can then use up to that amount of current for its charging circuitry. This current rating is primarily determined by the electromechanical components in the EVSE, such as conductors, relays, contactors, and the service connection.

The relationship between duty cycle and current is defined by two different equations depending on the current range specified; for a 6- to 51-A service, is:

$$\text{Duty cycle} = \frac{\text{Amps}}{0.6}$$

For a higher service in the 51- to 80-A range, is:

$$\text{Duty cycle} = \frac{\text{Amps}}{2.5} + 64$$
To demonstrate this relationship further, Table 5 shows some of the common service ratings.

<table>
<thead>
<tr>
<th>AMPS</th>
<th>DUTY CYCLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>8.3%</td>
</tr>
<tr>
<td>15</td>
<td>25%</td>
</tr>
<tr>
<td>30</td>
<td>50%</td>
</tr>
<tr>
<td>40</td>
<td>66.6%</td>
</tr>
<tr>
<td>65</td>
<td>90%</td>
</tr>
<tr>
<td>80</td>
<td>96%</td>
</tr>
</tbody>
</table>

In this design, the PWM is generated by a timer module on the MSP430™ MCU. The current rating can typically be set as a permanent value in the firmware because it is so tightly coupled to the external hardware.

Advanced EVSEs with a human machine interface (HMI) can enable the current to be derated if the service line is unable to provide enough current with a stable voltage. A significant voltage drop as a result of wire loss is possible in these high current applications.

2.2.3.1.1 Control Pilot Signal States

The EVSE connection and negotiation occurs through various states of the PWM signal and load resistances of the vehicle. Table 6 highlights these states:

<table>
<thead>
<tr>
<th>STATE</th>
<th>PILOT HIGH VOLTAGE</th>
<th>PILOT LOW VOLTAGE</th>
<th>FREQUENCY</th>
<th>RESISTANCE</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>State A</td>
<td>12 V</td>
<td>N/A</td>
<td>DC</td>
<td>N/A</td>
<td>Not connected</td>
</tr>
<tr>
<td>State B</td>
<td>9 V, –12 V</td>
<td>1 kHz</td>
<td>2.74 kΩ</td>
<td></td>
<td>EV connected, ready to charge</td>
</tr>
<tr>
<td>State C</td>
<td>6 V, –12 V</td>
<td>1 kHz</td>
<td>882 Ω</td>
<td></td>
<td>EV charging</td>
</tr>
<tr>
<td>State D</td>
<td>3 V, –12 V</td>
<td>1 kHz</td>
<td>246 Ω</td>
<td></td>
<td>EV charging, ventilation required</td>
</tr>
<tr>
<td>State E</td>
<td>0 V</td>
<td>0 V</td>
<td>N/A</td>
<td>—</td>
<td>Error</td>
</tr>
<tr>
<td>State F</td>
<td>N/A</td>
<td>–12 V</td>
<td>N/A</td>
<td>—</td>
<td>Unknown error</td>
</tr>
</tbody>
</table>

States A, B, and C are the core functionality and define the normal operation. An EVSE typically performs several self-tests upon initially powering on and then enters State A. When ready, the normal connection process follows several steps:

1. The EVSE puts 12 V on the pilot wire. This transmission signals the vehicle when the plug is connected.
2. When the plug is connected, the vehicle places a 2.74-kΩ load on the pilot line, which drops the voltage to 9 V.
3. The EVSE moves to State B, where it enables the PWM, which signals the vehicle how much current it can draw. The EVSE also closes the relays, providing power to the vehicle.
4. The vehicle starts to draw power and switches to the 822-Ω load, which drops the voltage to 6 V, signaling the EVSE that charging has started.
5. Most vehicles continue to pull low amounts of power in state C, even when fully charged, so the charging process is ended by unplugging the cable, which returns the voltage to 12 V. The EVSE measures this process and closes the relays and returns to State A.

Additional error handling such as missing diodes in the vehicle or an improper connection can be detected and handled by the EVSE by cutting the power, as well.
### 2.2.3.1.2 Control Pilot Signal Circuit

The pilot signal is required to travel down several meters of cable and through a load resistance. The pilot signal is also a bipolar ±12-V signal, which requires special consideration. To accommodate these parameters, an amplifier with a wide input range and reasonable power output is selected. The TLV1805 device has a voltage rating of ±18 V and a current rating of 475 mA, making it suitable for the application. In addition, while most EVSEs do not require an automotive qualification, a Q1-rated variant of the TLV1805-Q1 device exists, if this feature is desired.

The amplification circuit is a simple rail-to-rail output configuration of the TLV1805 device, with the MCU I/O driving the positive input. The output of the pilot amplifier is also fed into a simple voltage divider so that the MCU can measure the voltage during operation and detect the load resistance of the vehicle. Figure 3 shows the full schematic of this subsystem.

![Control Pilot Signal Generator Circuit](image)

To validate the architecture, the design was tested in the TINA-TI™ software from TI, which is a spice-based simulation tool.
2.2.4 Relay Drive and Latch Detect

The primary functionality of the EVSE is the reliable control of large currents directed toward an electric vehicle at the mains voltage. In a normal use case, the relay or contactor must be held closed for several hours to fully charge a vehicle; however, they cannot be latching because of safety concerns. If something fails in the control system, they must fail open. These high current relays or contactors can typically draw 10s to 100s of milliamps as an inductive load, requiring specific drive architectures.

Because of the amount of time that a relay or contactor requires to remain powered, an efficient drive solution is preferred to the typical Darlington array, or even discrete transistor configuration. For this reason, the DRV110 current controller is selected to drive the relays or contactors in the design. The DRV110 device is designed to regulate the current with a well-controlled waveform to reduce power dissipation.

Relays and contactors use electromechanical solenoids for their operation. Activation starts when EN pin voltage is pulled high either by an external driver or internal pullup. Once the EN pin is driven to GND, the DRV110 device allows the solenoid current to decay to zero. The solenoid current is ramped up fast to ensure opening of the relay or contactor. After initial ramping, the solenoid current is kept at a peak value to ensure correct operation, after which the current is reduced to a lower hold level to avoid thermal problems and reduce power dissipation.

![Figure 4. Typical Current Waveform Through the Solenoid](image)

For safety reasons, detecting the output voltage of the primary relay is critical. The contacts can experience arcing and become fused together, providing power to the plug even when the system is not powering it. Checking that the operation completed correctly is important and should be done every time the relay is opened. To implement this check, the ISO1212 fully-integrated, isolated digital-input receiver is used to sense line voltage.

The outputs (OUT1 and OUT2) from the ISO1212 device are GPIO-level DC signals that are high when voltage is present and are fed directly into the MCU for fault detection.
2.3 **Highlighted Products**

2.3.1 **UCC28740**

The UCC28740 device is a flyback power-supply controller which provides high-performance voltage regulation using an optically coupled feedback signal from a secondary-side voltage regulator. The device provides accurate constant-current regulation using primary-side feedback. The controller operates in discontinuous-conduction mode (DCM) with valley-switching to minimize switching losses. The control law scheme combines frequency with primary peak-current amplitude modulation to provide high conversion efficiency across the load range. The control law provides a wide dynamic operating range of output power which allows the power-supply designer to easily achieve less than 30-mW standby power dissipation using a standard shunt-regulator and optocoupler.

2.3.2 **TLV1805**

The TLV1805 comparator features rail-to-rail inputs with a push-pull output stage that operates at supply voltages as high as 40 V or ±20 V. The rail-to-rail input stage enables detection of signals close to the supply and ground while the push-pull output stage creates fast transition edges to either supply rail. A low supply current of 135 μA per channel with small, space-saving packages, makes these comparators versatile for use in a wide range of applications, from portable to industrial.

2.3.3 **DRV110**

The DRV110 device provides a PWM current controller for use with solenoids. The device provides a quick ramp to a high peak current value to ensure opening of the valve or relay. The current is held for a programmable time and then lowered to the hold current value to maintain the open state of the valve or relay while reducing the total current consumption. Peak current duration, peak current amount, hold current amount (in the 14-pin package), and PWM frequency can all be controlled by external components or used at default levels by omitting these components (except peak current duration).

Enable and disable of the switch is controlled by the EN pin. The EN pin contains an internal resistor network to set the pin to logic HIGH when the EN pin is floating. This feature can be used for situations where a control signal is not required and the solenoid is only energized when a supply voltage is present. Such applications could be valves or contactors.

2.3.4 **ISO1212**

The ISO1211 and ISO1212 devices are fully-integrated, isolated digital-input receivers with IEC 61131-2 Type 1, 2, and 3 characteristics. The devices receive 24-V to 60-V digital-input signals and provide isolated digital outputs. No field-side power supply is required. An external resistor, $R_{\text{SENSE}}$, on the input-signal path precisely sets the limit for the current drawn from the field input based on an internal feedback loop. The voltage transition thresholds are compliant with Type 1, 2, and 3 and can be increased further using an external resistor, $R_{\text{THR}}$.

The ISO121x devices use an ON-OFF keying (OOK) modulation scheme to transmit the digital data across a silicon-dioxide based isolation barrier. The transmitter sends a high frequency carrier across the barrier to represent one digital state and sends no signal to represent the other digital state. The receiver demodulates the signal after advanced signal conditioning and produces the output through a buffer stage.
2.3.5 TL431LI

The TL431LI device is a three-terminal adjustable shunt regulator, with specified thermal stability over applicable automotive, commercial, and military temperature ranges. The output voltage can be set to any value between $V_{\text{REF}}$ (approximately 2.495 V) and 36 V, with two external resistors. These devices have a typical output impedance of 0.3 $\Omega$. Active output circuitry provides a very sharp turn-on characteristic, making these devices excellent replacements for Zener diodes in many applications, such as onboard regulation, adjustable power supplies, and switching power supplies. This device is a pin-to-pin alternative to the industry standard TL431, with optimized $I_{\text{REF}}$ and $I_{\text{I(dev)}}$ performance. The lower $I_{\text{REF}}$ and $I_{\text{I(dev)}}$ values enable designers to achieve higher system accuracy and lower leakage current.

2.3.6 LP2951

The LP2951 device is a bipolar, low-dropout voltage regulator that can accommodate a wide input supply-voltage range of up to 30 V. The 8-pin LP2951 device is able to output either a fixed or adjustable output from the same device. By tying the OUTPUT and SENSE pins together, and the FEEDBACK and VTAP pins together, the LP2951 device outputs a fixed 5 V, 3.3 V, or 3 V (depending on the version). Alternatively, by leaving the SENSE and VTAP pins open and connecting FEEDBACK to an external resistor divider, the output can be set to any value between 1.235 V to 30 V.

The 8-pin LP2951 device also offers additional functionality that makes it particularly suitable for battery-powered applications. For example, a logic-compatible shutdown feature allows the regulator to be put in standby mode for power savings. In addition, there is a built-in supervisor reset function in which the ERROR output goes low when $V_{\text{OUT}}$ drops by 6% of its nominal value for whatever reasons – due to a drop in $V_{\text{IN}}$, current limiting, or thermal shutdown.

2.3.7 TPS715A

The TPS715A low-dropout (LDO) voltage regulator offers the benefits of high-input voltage, low-dropout voltage, low-power operation, and miniaturized packaging. The devices operate over an input range of 2.5 V to 24 V and are stable with any capacitor ($\geq 0.47 \mu F$). The high maximum input voltage combined with excellent power dissipation capability makes this device particularly well-suited to industrial and automotive applications.

A PMOS pass element functions as a low-value resistor. The low dropout voltage, typically 670 mV at 80 mA of load current, is directly proportional to the load current. The low quiescent current (3.2 $\mu A$ typically) is nearly constant over the entire range of output load current (0 mA to 80 mA).

2.3.8 TPS7A30

The TPS7A30 series of devices are negative, high voltage (~35 V), ultra-low noise (15.1 $\mu V_{\text{RMS}}, 72$-dB) linear regulators that can source a maximum load of 200 mA. The TPS7A30 family of devices are wide $V_{\text{IN}}$, low-noise, 150-mA linear regulators (LDOs). These devices feature an enable pin, programmable soft-start, current limiting, and thermal protection circuitry that allow the device to be used in a wide variety of applications. As bipolar-based devices, the TPS7A30 devices are ideal for high-accuracy, high-precision applications at higher voltages.

2.3.9 LM79L

The LM79LXXAC series of 3-terminal negative $-5$ V, $-12$ V, and $-15$ V voltage regulators with output current capabilities in excess of 100 mA. These devices were designed using the latest computer techniques for optimizing the packaged IC thermal and electrical performance. The LM79LXXAC series, when combined with a minimum output capacitor of 0.1 $\mu F$, exhibits an excellent operating area protection transient response, a maximum line regulation of 0.01% $V_{\text{OUT}}/\text{mA}$.
2.3.10 **TPS561201**

The TPS561201 and TPS561208 devices are 1-A synchronous step-down converters. The proprietary D-CAP2 mode control supports low ESR output capacitors such as specialty polymer capacitors and multilayer ceramic capacitors without complex external compensation circuits. The fast transient response of D-CAP2 mode control can reduce the output capacitance required to meet a specific level of performance.

2.3.11 **TPS62172**

The TPS6217x device family are easy to use synchronous step-down DC/DC converters optimized for applications with high-power density. A high switching frequency of typically 2.25 MHz allows the use of small inductors and provides fast transient response as well as high-output voltage accuracy by utilization of the DCS-Control™ topology.

In power save mode, the devices show quiescent current of about 17 μA from V\text{IN}. Power save mode, entered automatically and seamlessly if the load is small, maintains high efficiency over the entire load range. In shutdown mode, the device is turned off and shutdown current consumption is less than 2 μA.

2.3.12 **TLV704**

The TLV704 series belong to a family of ultra-low I\text{Q} LDO regulators. I\text{Q} remains fairly constant over the complete output load current and temperature range. The devices are ensured to operate over a temperature range of −40°C to 125°C.

2.3.13 **TLV760**

The TLV760 is an integrated linear-voltage regulator featuring operation from an input as high as 30 V. The TLV760 has a maximum dropout of 1.2 V at the full 100-mA load across operating temperature. Standard packaging for the TLV760 is the 3-pin SOT23 package.

The TLV760 is available in 3.3 V, 5 V, 12 V and 15 V. The SOT-23 packaging of the TLV760 series allows the device to be used in space-constrained applications. The TLV760 is a small size alternative to the LM78Lxx series and similar devices.

2.3.14 **CSD19534Q5A**

This 100 V, 12.6 mΩ, SON 5 mm × 6 mm NexFET™ power MOSFET is designed to minimize losses in power conversion applications.
3 Hardware, Testing Requirements, and Test Results

3.1 Getting Started With Hardware

Figure 5 shows the top view of the board and different sections of the TIDA-010071 PCB.

Table 7. Connectors and Jumpers on PCB

<table>
<thead>
<tr>
<th>CONNECTOR OR JUMPER NAME</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACIN</td>
<td>Input AC connector</td>
</tr>
<tr>
<td>RELAY_ISO</td>
<td>ISO1212 device to relay connector</td>
</tr>
<tr>
<td>RELAY_OUT</td>
<td>DRV110 device to relay connector</td>
</tr>
<tr>
<td>PILOT OUT</td>
<td>Control pilot signal</td>
</tr>
<tr>
<td>J1</td>
<td>13-V flyback output</td>
</tr>
<tr>
<td>J2</td>
<td>Enable and disable jumper for input to the TPS715A device (U4)</td>
</tr>
<tr>
<td>J3</td>
<td>Enable and disable jumper for input to the TLV760 device (U3)</td>
</tr>
<tr>
<td>J4</td>
<td>+12-V output of the TPS715A device (U4)</td>
</tr>
<tr>
<td>J5</td>
<td>+12-V output of the TLV760 device (U3)</td>
</tr>
<tr>
<td>J6</td>
<td>Enable and disable jumper for input to the TLV704 device (U5)</td>
</tr>
<tr>
<td>J7</td>
<td>Enable and disable jumper for input to the LP2951 device (U6)</td>
</tr>
<tr>
<td>J8</td>
<td>+5-V output of the TLV704 device (U5)</td>
</tr>
<tr>
<td>J9</td>
<td>+5-V output of the LP2951 device (U6)</td>
</tr>
<tr>
<td>J10</td>
<td>Enable and disable jumper for input to the TPS7A30 device (U7)</td>
</tr>
<tr>
<td>J11</td>
<td>−12-V output of the TPS7A30 device (U7)</td>
</tr>
</tbody>
</table>
Table 7. Connectors and Jumpers on PCB (continued)

<table>
<thead>
<tr>
<th>CONNECTOR OR JUMPER NAME</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>J12</td>
<td>Enable and disable jumper for input to the LM79L device (U8)</td>
</tr>
<tr>
<td>J13</td>
<td>–5-V output of the LM79L device (U8)</td>
</tr>
<tr>
<td>J14</td>
<td>Enable and disable jumper for input to the TPS7A30 device (U9)</td>
</tr>
<tr>
<td>J15</td>
<td>–5-V output of the TPS7A30 device (U9)</td>
</tr>
<tr>
<td>J16</td>
<td>Enable and disable jumper for input to the TPS561201 device (U10)</td>
</tr>
<tr>
<td>J17</td>
<td>+3.3-V output of the TPS561201 device (U10)</td>
</tr>
<tr>
<td>J18</td>
<td>Enable and disable jumper for input to the TPS62172 device (U11)</td>
</tr>
<tr>
<td>J19</td>
<td>+3.3-V output of the TPS62172 device (U11)</td>
</tr>
<tr>
<td>J20 and J21</td>
<td>40-pin LaunchPad header</td>
</tr>
<tr>
<td>J22</td>
<td>Enable and disable jumper for input to the DRV110 device (U13)</td>
</tr>
</tbody>
</table>
3.2 Testing and Results

3.2.1 Test Setup

Figure 6 shows a block diagram of the external component arrangement and final connections in the test setup.

Figure 6. External Component Connections With TIDA-010071 Hardware

The test setup for the linear regulator and converters consists of the TIDA-010071 board, DC supply, digital multimeter, electronic load, voltage and current probe as Figure 7 shows:
Figure 7. Test Setup for Linear Regulator and Converters in TIDA-010071

Device Under Test (DUT)
The oscilloscope analog signal bandwidth should be greater than 400 times the switching frequency.
The oscilloscope should have higher memory depth and sampling rate to capture ripple waveform accurately (at least 4 GSPS, memory depth > 1Mpts).
Oscilloscope probe terminated to 50 Ω.

The tests conducted for this design follow:
• Device efficiency and system efficiency at various loads
• Ripple voltage, ripple frequency at full and light load conditions, output voltage accuracy
• Load transient response

To test the previous conditions, set the 61/2 DMM with the following settings to average the source and instrument error:
• Slow filter – 7 seconds per reading
• Number of samples – 50 (approximately 6 minutes)
3.2.2 Test Results

3.2.2.1 Isolated AC/DC Power Supply Based on UCC28740

This section shows test data for efficiency over full scale load variation, output voltage regulation, output ripple, cross regulation and transient load response waveforms, as well as thermal performance.

3.2.2.1.1 Efficiency and Output Voltage Cross Regulation

Figure 8. Output Power vs Efficiency at 120 V AC, 60 Hz and 230 V AC, 50 Hz

<table>
<thead>
<tr>
<th>V_RMS (V)</th>
<th>I_RMS (mA)</th>
<th>P_IN (W)</th>
<th>V_IN (V)</th>
<th>I_IN (A)</th>
<th>V_OUT (V)</th>
<th>I_OUT (A)</th>
<th>P_OUT (W)</th>
<th>EFFICIENCY</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>250.1</td>
<td>14.712</td>
<td>12.85</td>
<td>0.494</td>
<td>-15.12</td>
<td>0.202</td>
<td>8.32</td>
<td>0.310</td>
</tr>
<tr>
<td>230.7</td>
<td>13.275</td>
<td>12.85</td>
<td>0.389</td>
<td>-15.03</td>
<td>0.200</td>
<td>8.27</td>
<td>0.309</td>
<td>10.568</td>
</tr>
<tr>
<td>209.9</td>
<td>11.758</td>
<td>12.85</td>
<td>0.299</td>
<td>-14.91</td>
<td>0.199</td>
<td>8.22</td>
<td>0.307</td>
<td>9.325</td>
</tr>
<tr>
<td>202.7</td>
<td>11.22</td>
<td>12.85</td>
<td>0.252</td>
<td>-14.69</td>
<td>0.245</td>
<td>8.26</td>
<td>0.250</td>
<td>8.902</td>
</tr>
<tr>
<td>173.2</td>
<td>9.19</td>
<td>12.85</td>
<td>0.201</td>
<td>-14.73</td>
<td>0.205</td>
<td>8.24</td>
<td>0.196</td>
<td>7.210</td>
</tr>
<tr>
<td>142.5</td>
<td>7.07</td>
<td>12.85</td>
<td>0.151</td>
<td>-14.75</td>
<td>0.154</td>
<td>8.23</td>
<td>0.150</td>
<td>5.440</td>
</tr>
<tr>
<td>109</td>
<td>4.97</td>
<td>12.85</td>
<td>0.100</td>
<td>-14.78</td>
<td>0.101</td>
<td>8.2</td>
<td>0.100</td>
<td>3.596</td>
</tr>
<tr>
<td>69.1</td>
<td>2.86</td>
<td>12.85</td>
<td>0.05</td>
<td>-14.84</td>
<td>0.050</td>
<td>8.18</td>
<td>0.050</td>
<td>1.800</td>
</tr>
</tbody>
</table>

Table 9. Test Data at 230-V AC, 50-Hz AC Input

<table>
<thead>
<tr>
<th>V_RMS (V)</th>
<th>I_RMS (mA)</th>
<th>P_IN (W)</th>
<th>V_IN (V)</th>
<th>I_IN (A)</th>
<th>V_OUT (V)</th>
<th>I_OUT (A)</th>
<th>P_OUT (W)</th>
<th>EFFICIENCY</th>
</tr>
</thead>
<tbody>
<tr>
<td>230</td>
<td>175.8</td>
<td>14.66</td>
<td>12.85</td>
<td>0.494</td>
<td>-15.19</td>
<td>0.203</td>
<td>8.31</td>
<td>0.310</td>
</tr>
<tr>
<td>159.59</td>
<td>13.06</td>
<td>12.85</td>
<td>0.389</td>
<td>-15.08</td>
<td>0.201</td>
<td>8.26</td>
<td>0.308</td>
<td>10.582</td>
</tr>
<tr>
<td>143.86</td>
<td>11.56</td>
<td>12.85</td>
<td>0.299</td>
<td>-14.96</td>
<td>0.199</td>
<td>8.2</td>
<td>0.306</td>
<td>9.333</td>
</tr>
<tr>
<td>137.9</td>
<td>11.05</td>
<td>12.85</td>
<td>0.252</td>
<td>-14.71</td>
<td>0.245</td>
<td>8.21</td>
<td>0.249</td>
<td>8.887</td>
</tr>
<tr>
<td>116.76</td>
<td>9.12</td>
<td>12.85</td>
<td>0.201</td>
<td>-14.76</td>
<td>0.205</td>
<td>8.21</td>
<td>0.195</td>
<td>7.211</td>
</tr>
<tr>
<td>93.97</td>
<td>7.09</td>
<td>12.85</td>
<td>0.151</td>
<td>-14.77</td>
<td>0.154</td>
<td>8.19</td>
<td>0.149</td>
<td>5.435</td>
</tr>
<tr>
<td>69.87</td>
<td>5.06</td>
<td>12.85</td>
<td>0.100</td>
<td>-14.8</td>
<td>0.101</td>
<td>8.15</td>
<td>0.099</td>
<td>3.590</td>
</tr>
<tr>
<td>44.07</td>
<td>2.92</td>
<td>12.85</td>
<td>0.050</td>
<td>-14.83</td>
<td>0.050</td>
<td>8.14</td>
<td>0.050</td>
<td>1.795</td>
</tr>
</tbody>
</table>

Table 10. Output Voltage Cross Regulation at 120-V AC, 60-Hz AC Input

<table>
<thead>
<tr>
<th>I_i1 (A)</th>
<th>I_o1 (A)</th>
<th>I_o2 (A)</th>
<th>V_i1 (V)</th>
<th>V_o1 (V)</th>
<th>V_i2 (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.494</td>
<td>0.201</td>
<td>0.310</td>
<td>12.85</td>
<td>-15.14</td>
<td>8.32</td>
</tr>
<tr>
<td>0</td>
<td>0.192</td>
<td>0.292</td>
<td>12.85</td>
<td>-14.18</td>
<td>7.84</td>
</tr>
<tr>
<td>0.494</td>
<td>0.202</td>
<td>0</td>
<td>12.85</td>
<td>-15.16</td>
<td>11.59</td>
</tr>
<tr>
<td>0.494</td>
<td>0</td>
<td>0.311</td>
<td>12.85</td>
<td>-22.47</td>
<td>8.35</td>
</tr>
</tbody>
</table>
Table 10. Output Voltage Cross Regulation at 120-V AC, 60-Hz AC Input (continued)

<table>
<thead>
<tr>
<th>I_{13} (A)</th>
<th>I_{15} (A)</th>
<th>I_{7} (A)</th>
<th>V_{13} (V)</th>
<th>V_{15} (V)</th>
<th>V_{7} (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0.292</td>
<td>12.85</td>
<td>-17.62</td>
<td>7.68</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>12.85</td>
<td>-15.21</td>
<td>8.17</td>
</tr>
<tr>
<td>0.494</td>
<td>0</td>
<td>0</td>
<td>12.85</td>
<td>-21.59</td>
<td>10.88</td>
</tr>
<tr>
<td>V_{OUT,MAX}</td>
<td>12.85</td>
<td>-13.61</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V_{OUT,MIN}</td>
<td>12.85</td>
<td>-22.47</td>
<td></td>
<td></td>
<td>7.68</td>
</tr>
<tr>
<td>ΔV</td>
<td>0</td>
<td>8.86</td>
<td></td>
<td></td>
<td>3.91</td>
</tr>
</tbody>
</table>

3.2.2.1.2 Output Voltage Ripple and Startup Waveforms

Figure 9. Output Voltage Ripple at No Load With 120-V AC, 60-Hz AC Input

Figure 10. Output Voltage Ripple at Full Load With 120-V AC, 60-Hz AC Input

Figure 11. Startup at No Load With 120-V AC, 60-Hz AC Input

Figure 12. Startup at Full Load With 120-V AC, 60-Hz AC Input
3.2.2.1.3 Transient Response Waveforms

Figure 13. Transient on 13-V Rail From No Load to Full Load at 120-V AC, 60-Hz AC Input

Figure 14. Transient on 13-V Rail From Full Load to No Load at 120-V AC, 60-Hz AC Input

Figure 15. Transient on 7-V Rail From No Load to Full Load at 120-V AC, 60-Hz AC Input

Figure 16. Transient on 7-V Rail From Full Load to No Load at 120-V AC, 60-Hz AC Input
3.2.2.1.4 Thermal Performance

![Figure 17. Top View of AC/DC Stage at 120-V AC, 60-Hz AC Input](image1)

![Figure 18. Bottom View of AC/DC Stage at 120-V AC, 60-Hz AC Input](image2)

3.2.2.2 Output Voltage Accuracy and Transient Response of LDOs Powering TLV1805

Table 11 shows the LDOs used to power the TLV1805 device used as control pilot generator.

<table>
<thead>
<tr>
<th>VOLTAGE RAIL</th>
<th>SELECTED DEVICE</th>
<th>OUTPUT VOLTAGE ACCURACY</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 V</td>
<td>TPS715A or TLV760(1)</td>
<td>≤ ±2%</td>
</tr>
<tr>
<td>–12 V</td>
<td>TPS7A30</td>
<td>≤ ±2%</td>
</tr>
</tbody>
</table>

(1) The TLV760 device can be used to power the control pilot signal generator for cost-sensitive applications.
Figure 19 to Figure 21 show the transient response waveforms for the devices from no load to 80-mA load.

**Figure 19. TPS715A Transient Response From No Load to 80-mA Load**

**Figure 20. TPS7A30 Transient Response From No Load to 80-mA Load**

**Figure 21. TLV760 Transient Response From No Load to 80-mA Load**
3.2.2.3  Test Results for TPS561201 and TPS62172 DC/DC

Figure 22 to Figure 29 show the test results for the TPS561201 and TPS62172 DC/DC.

Figure 22. Load Current vs Efficiency for TPS561201 and TPS62172 With 3.3-V DC Output

Figure 23. Output Voltage Accuracy for TPS561201 and TPS62172 With 3.3-V DC Output

Figure 24. Output Voltage Ripple for TPS561201 With 3.3-V DC Output at No Load

Figure 25. Output Voltage Ripple for TPS62172 With +3.3-V DC Output at No Load
3.2.2.4 **TLV1805-based Control Pilot Interface**

This section shows test data for control pilot signal logic high and low voltage, pulse width, and frequency.

3.2.2.4.1 **TLV1805 Output Rise and Fall Time**

Figure 30 and Figure 31 show the rise and fall times of the TLV1805 control pilot signal generator.
3.2.2.4.2 Control Pilot Signal Voltage Accuracy in Different States

Figure 32 through Figure 35 show the control pilot signal voltage accuracy in different states.

Figure 32. Control Pilot Signal Voltage Accuracy in State A

Figure 33. Control Pilot Signal Voltage Accuracy in State B

Figure 34. Control Pilot Signal Voltage Accuracy in State C

Figure 35. Control Pilot Signal Voltage Accuracy in State D
3.2.2.5 **DRV110-based Relay Drive**

This section is comprised of test data for the average power dissipation in relay (T9AS5D22-12), gate drive, and relay current waveform at hold (9 V) and drive (12 V) voltage.

### 3.2.2.5.1 Average Power Dissipation Comparison Between Constant Voltage Drive and Controlled Current Drive Using DRV110

Figure 36 to Figure 39 illustrate the average power dissipation comparison between CV drive and CC drive using the DRV110 device.

#### Figure 36. Relay Average Power Dissipation at 12-V Drive Voltage Driven Using Constant Voltage Source

#### Figure 37. Relay Average Power Dissipation at 9-V Hold Voltage Driven Using Constant Voltage Source

#### Figure 38. Relay Average Power Dissipation at 12-V Drive Voltage Driven Using DRV110

#### Figure 39. Relay Average Power Dissipation at 9-V Hold Voltage Driven Using DRV110
3.2.2.5.2 **DRV110 Enable Pin, Gate Drive and Relay Current**

Figure 40 through Figure 42 show the DRV110 enable pin, gate drive, and relay current waveforms.
3.2.2.6  ISO1212-based Isolated Line Voltage Sensing

Figure 43 and Figure 44 show the ISO1212-based isolated line voltage sensing waveforms.
4 Design Files

4.1 Schematics
To download the schematics, see the design files at TIDA-010071.

4.2 Bill of Materials
To download the bill of materials (BOM), see the design files at TIDA-010071.

4.3 PCB Layout Recommendations

4.3.1 Layout Prints
To download the layer plots, see the design files at TIDA-010071.

4.4 Altium Project
To download the Altium Designer® project files, see the design files at TIDA-010071.

4.5 Gerber Files
To download the Gerber files, see the design files at TIDA-010071.

4.6 Assembly Drawings
To download the assembly drawings, see the design files at TIDA-010071.

5 Software Files
To download the software files, see the design files at TIDA-010071.

6 Related Documentation
1. Texas Instruments, TIDA-00637: Level 1&2 Electric Vehicle Service Equipment Reference Design
2. Texas Instruments, UCC28740 Constant-Voltage Constant-Current Flyback Controller Using Opto-Coupled Feedback Data Sheet
3. Texas Instruments, TLV1805 40V, Rail-to-Rail Input, Push-Pull Output, High Voltage Comparator with Shutdown Data Sheet
4. Texas Instruments, DRV110 Power-Saving Solenoid Controller With Integrated Supply Regulation Data Sheet
5. Texas Instruments, ISO121x Isolated 24-V Digital Input Receivers for Digital Input Modules Data Sheet
6. Texas Instruments, TL43xLx Programmable Shunt Regulator with Optimized Reference Current Data Sheet
7. Texas Instruments, LP2951 Adjustable Micropower Voltage Regulators With Shutdown Data Sheet
8. Texas Instruments, TPS715A-NM 24-V High Input Voltage, Micropower, 80-mA LDO Voltage Regulator Data Sheet
10. Texas Instruments, LM79LXXAC Series 3-Terminal Negative Regulators Data Sheet
11. Texas Instruments, TPS56120x 4.5-V to 17-V Input, 1-A Synchronous Step-Down Voltage Regulator in 6-Pin SOT-23 Data Sheet
12. Texas Instruments, TPS6217x 3-V to 17-V, 0.5-A Step-Down Converters With DCS-Control™ Data Sheet
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7 **About the Author**

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8 **Acknowledgment**

The authors would like to thank Jayanth Rangaraju and Bart Basile for their critical feedback on different stages of this design.
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