How to Design a Boost Converter With the TPS61170

Jeff Falin

Design Example

The following design example helps a user design a 12-V to 24-V power supply using the TPS61170 boost converter integrated circuit (IC). Figure 1 shows the power supply circuit.

![Figure 1. 12-V to 24-V Power Supply](image)

Table 1 gives the performance specifications for the reference design.

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<th>Parameter</th>
<th>Conditions</th>
<th>Min</th>
<th>Nom</th>
<th>Max</th>
<th>Unit</th>
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<td><strong>INPUT and AMBIENT CHARACTERISTICS</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>$V_{IN}$</td>
<td>Input voltage</td>
<td>11</td>
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<td>V</td>
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<td>$F_S$</td>
<td>Switching frequency</td>
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<tr>
<td>$T_A$</td>
<td>Ambient temperature</td>
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<td><strong>OUTPUT CHARACTERISTICS</strong></td>
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<td></td>
</tr>
<tr>
<td>$V_{OUT}$</td>
<td>Output voltage</td>
<td>23</td>
<td>24</td>
<td>25</td>
<td>V</td>
</tr>
<tr>
<td>Load regulation</td>
<td>$V_{IN} = 12$ V, $10$ mA $&lt; I_O &lt; 300$ mA</td>
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<td></td>
<td></td>
<td>%</td>
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<tr>
<td>$V_{RIPPLE}$</td>
<td>Output voltage ripple</td>
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<td>mVpp</td>
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<tr>
<td>$I_O$</td>
<td>Output current</td>
<td>1</td>
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<td>300</td>
<td>mA</td>
</tr>
<tr>
<td>$\eta$</td>
<td>Efficiency</td>
<td>92%</td>
<td></td>
<td></td>
<td>%</td>
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<td><strong>TRANSIENT RESPONSE</strong></td>
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<tr>
<td>$\Delta I_{TRAN}$</td>
<td>Load step</td>
<td>250</td>
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<td></td>
<td>mA</td>
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<td>$\Delta I_{TRAN}/\Delta t$</td>
<td>Load slew rate</td>
<td>0.20</td>
<td></td>
<td></td>
<td>A/µs</td>
</tr>
<tr>
<td>$\Delta V_{TRAN}$</td>
<td>$V_O$ undershoot</td>
<td></td>
<td></td>
<td>500</td>
<td>mV</td>
</tr>
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1. DUTY CYCLE: Use data sheet (SLVS789) Equation 5 to estimate the maximum duty cycle, which occurs at minimum input voltage. This value cannot exceed the IC’s maximum duty cycle per the datasheet.

\[
D_{\text{MAX}} = \frac{V_{\text{OUT}} - V_{\text{IN(MIN)}}}{V_{\text{OUT}}} = \frac{24 \text{ V} - 11 \text{ V}}{24 \text{ V}} = 55\%
\]  

(1)

2. \(I_{\text{OUT(MAX)}}\) and \(I_{\text{IN(DC)}}\): First, use data sheet Equation 4 to determine whether the internally current-limited TPS61170 can provide the desired output current.

At \(I_{\text{OUT(MAX)}}\), the current through the switch hits the switch’s current limit, \(I_{\text{LIM}}\). Expressed mathematically, the maximum average (DC) input current, \(I_{\text{IN(DC-MAX)}}\), plus 1/2 the peak-to-peak inductor ripple current, \(I_P\), equals \(I_{\text{LIM}}\), so \(I_{\text{IN(DC-MAX)}} = I_{\text{LIM}} - I_P/2\) at \(I_{\text{OUT(MAX)}}\). But, for stable power supply operation and to minimize EMI, \(I_P\) must be no more than a fraction, \(K_{\text{IND}} = 20-40\%\), of \(I_{\text{IN(DC)}}\), so \(I_{\text{IN(DC-MAX)}} = I_{\text{LIM}}(1 + K_{\text{IND}}/2)\). Solving for \(I_{\text{IN(DC-MAX)}}\) gives \(I_{\text{IN(DC)}} = I_{\text{LIM}}(1 + K_{\text{IND}}/2)\) at \(I_{\text{OUT(MAX)}}\). Assuming estimated efficiency \(\eta_{\text{est}} = 92\%\) at \(V_{\text{IN(MIN)}} = 11 \text{ V}\) and \(K_{\text{IND}} = 0.4\),

\[
I_{\text{OUT(MAX)}} = \frac{V_{\text{IN}} \times I_{\text{LIM}} \times \eta_{\text{est}}}{(1 + K_{\text{IND}}/2) \times V_{\text{OUT}}} = \frac{11 \text{ V} \times 0.96 \text{ A} \times 92\%}{(1 + 0.4/2) \times 24} = 337 \text{ mA}
\]

Because the application does not require the maximum output current computed by Equation 2, simply use data sheet Equation 6 to find \(I_{\text{IN(DC)}}\) at the estimated efficiency and desired output current, \(I_{\text{OUT}}\).

\[
I_{\text{IN(DC)}} = \frac{V_{\text{OUT}} \times I_{\text{OUT}}}{V_{\text{IN(MIN)}} \times 0.92} = \frac{24 \text{ V} \times 0.3 \text{ A}}{(11 \text{ V} \times 0.92)} = 0.71 \text{ A}
\]

3. INDUCTOR: After solving data sheet Equation 3 for \(L\), the designer substituted \(f_{\text{S(MIN)}} = 1 \text{ MHz}\), the Schottky diode’s forward voltage, \(V_f = 0.5 \text{ V}\), Equation 3, \(V_{\text{IN(MIN)}} = 11 \text{ V}\) and \(I_p = 0.4 \times 0.6 \text{ A}\) to find the minimum \(L\) required to keep \(I_p = K_{\text{IND}} \times I_{\text{IN(DC)}}\).

\[
L \geq \frac{1}{\left[ F_{\text{S}} \times \left( \frac{1}{V_{\text{OUT}} + V_f - V_{\text{IN(MIN)}}} + \frac{1}{V_{\text{IN(MIN)}}} \right) \right] \times I_p}
\]

\[
= \frac{1}{1 \text{ MHz} \times \left( \frac{1}{24 \text{ V} + 0.5 \text{ V} - 11 \text{ V}} + \frac{1}{11 \text{ V}} \right) \times 0.4 \times 0.71 \text{ A}} = 21.3 \mu\text{H} \rightarrow 22 \mu\text{H}
\]

The designer selected the closest standard value, which is 22 \(\mu\text{H}\). When selecting an inductor, the two additional key specifications are its DC resistance (DCR) and its current rating, which is the lower of either its saturation current or its current for 40°C temperature rise. For this lower power converter, choosing an inductor with DCR less than 200 m\(\Omega\) minimizes these losses. The inductor current rating must be higher than \(I_{\text{IN(DC)}} + I_p/2 = 0.71 \text{ A} + (0.4 \times 0.71 \text{ A}) / 2 = 0.85 \text{ A}\). The designer selected SD6020-220 from Cooper, capable of 0.9 A with 122-m\(\Omega\) DCR.

4. FEEDBACK RESISTORS: Use data sheet Equation 2 to size the feedback resistors for the required output voltage. Although the data sheet recommends 10 k\(\Omega\) as an optimum value for \(R_2\), larger or smaller values can be used at the risk of noise being injected into FB or higher current lost through the FB resistors, respectively. After first trying 10 k\(\Omega\), the designer selected \(R_2 = 10.5 \text{ k}\(\Omega\) so that \(R_1\) computes close to a standard resistor value:

\[
R_1 = R_2 \times \left( \frac{V_{\text{OUT}}}{1.229 \text{ V}} - 1 \right) = 10.5 \text{ k}\(\Omega\) \times \left( \frac{24}{1.229 \text{ V}} - 1 \right) = 195 \text{ k}\(\Omega\) \rightarrow 196 \text{ k}\(\Omega\)
\]

(4)

5. SCHOTTKY DIODE: Even with an ideal printed-circuit board layout containing short traces to minimize stray inductance and capacitance, the switching node of the boost converter may exhibit ringing up to 30% higher than the output voltage. Therefore, the designer selected a 30-V-rated diode to accommodate such ringing. The designer also selected a diode with a thermal rating that is high enough to accommodate its power dissipation, which is approximately \(P_{\text{D(DIODE)}} = I_{\text{OUT}} \times V_f = 300 \text{ mA} \times 0.5 \text{ V} = 150 \text{ mW}\).

6. OUTPUT CAPACITORS: Use data sheet Equation 12 and the transient specification to size the output capacitance.

Assuming a ceramic output capacitor with negligible ESR and output ripple specification \(V_{\text{RIPPLE}} = 50 \text{ mVpp}\), data sheet Equation 12 indicates that the minimum output capacitance be
\[
C_{\text{OUT}} = \frac{(V_{\text{OUT}} - V_{\text{IN}}) \times I_{\text{OUT}}}{V_{\text{OUT}} \times F_s \times V_{\text{RIPPLE}}} = \frac{(24 \text{ V} - 12 \text{ V}) \times 0.300 \text{ A}}{24 \text{ V} \times 1.0 \text{ MHz} \times 50 \text{ mV}} = 3 \mu \text{F}
\]  
(5)

If a large ESR capacitor is used, then there is additional output ripple equal to \( V_{\text{RIPPLE, ESR}} = I_{\text{OUT}} \times \text{ESR} \). To meet the load transient specification and assuming a control loop bandwidth \( f_{\text{BW}} = 30 \text{ kHz} \), Equation 6 gives

\[
C_{\text{OUT}} = \frac{\Delta I_{\text{TRANS}}}{2\pi \times f_{\text{BW}} \times \Delta V_{\text{TRANS}}} = \frac{250 \text{ mA}}{2 \times \pi \times 30 \text{ kHz} \times 500 \text{ mV}} = 2.6 \mu \text{F}
\]  
(6)

The loop bandwidth assumption of 30 kHz may have to be modified later. The designer selected \( C_2 = 2 \times 2.2 \mu \text{F}, 50-\text{V output capacitors} \) (Figure 1).

7. COMPENSATING THE CONTROL LOOP: Data sheet equations 7 through 11 can be combined to give a simple mathematical model of the power supply’s small signal control loop, \( G_T(s) \).

\[
G_T(s) = \frac{1.229 \text{ V}}{V_{\text{OUT}}} \times G_{\text{EA}} \times 6 \text{ M} \Omega \times \frac{V_{\text{IN}} \times R_{\text{OUT}}}{V_{\text{OUT}} \times R_{\text{SENSOR}} \times 2} \times \left(1 + \frac{s}{2 \times \pi \times f_{p2}}\right) \times \left(1 - \frac{s}{2 \times \pi \times f_{\text{RHPZ}}}\right)
\]

Where

\[
f_{p2} = \frac{2}{2\pi \times R_{\text{OUT}} \times C_2} = \frac{2}{2\pi \times 80 \ \Omega \times 2 \times 2.2 \ \mu \text{F}} = 905 \text{ Hz}
\]

\[
f_{\text{RHPZ}} = \frac{R_{\text{OUT}}}{2\pi \times L} \times \left(\frac{V_{\text{IN}}}{V_{\text{OUT}}}\right)^2 = \frac{80 \ \Omega}{2\pi \times 22 \ \mu \text{H}} \times \left(\frac{12}{24}\right)^2 = 136 \text{ kHz}
\]

\[
f_{p1} = \frac{1}{2\pi \times 6 \text{ M} \Omega \times C_3}
\]

\[
f_z = \frac{1}{2\pi \times R_3 \times C_3}
\]

(7)

\( G_{\text{EA}} \) is the amplifier transconductance and can be found in the data sheet electrical specifications table and \( R_{\text{OUT}} = V_{\text{OUT}}/I_{\text{OUT}} \). For current mode boost power supplies, the inductor is not part of the control loop, and the output capacitor sets the dominant pole, \( f_{p2} \). If the RHPZ is high enough in frequency (i.e., \( L \) is not too large), simply setting the compensation zero, \( f_z \), equal to the dominant pole, \( f_{p2} \), stabilizes the loop. Assuming \( R_3 = 10 \ \text{k} \Omega \) per the data sheet recommendation and \( R_{\text{SENSOR}} = 200 \ \text{m} \Omega \), its approximate maximum value, setting \( f_z = f_{p2} \) gives \( C_3 = 17.6 \ \text{nF} \) which is replaced by the standard value of 15 nF. Figure 2 shows the Mathcad™ gain and phase of the power stage, \( G_T(s) \), with \( s = j \times 2 \pi \times f \).
Figure 2. Total Loop Gain and Phase With R3 = 10 kΩ and C3 = 15 nF

Although the loop is stable with almost 90 degrees of phase margin and small signal control loop bandwidth, $f_{BW}$, of 20 kHz, components R3 and C3 are not optimized to give the highest bandwidth, and therefore the smallest output capacitance to meet the load transient requirement. In fact, maximizing the loop bandwidth using this method requires iteratively increasing R3 and/or decreasing C3 to meet the load transient specification.

By separating the power stage and error amplifier components from data sheet equations 7 through 11, the designer can directly size R3 and C3 for a given $f_{BW}$ without an interactive, trial and error process. $G_{PW}$ gives the power stage small signal transfer function.

$$G_{PW}(s) = \frac{R_{OUT} \times (V_{IN})}{2 \times R_{SENSE} \times V_{OUT}} \times \left( \frac{1 - s}{2 \times \pi \times f_{RHPZ}} \right) \times He(s)$$  \hspace{1cm} (8)

**Equation 8** ignores the ESR zero, $f_{Z}$, because low ESR ceramic output capacitors produce a zero at frequencies above interest. If tantalum or aluminum electrolytic output capacitors are used, then an additional zero created by the output capacitor and ESR must be included in equation 8 in the form $f_{ZESR} = 1 + s/(2 \times \pi \times \text{ESR} \times C_2)$. The simplest way to handle this potentially low frequency zero is to cancel it with a pole by connecting an appropriately sized capacitor from COMP to ground. Usually, the stray board capacitance or an actual capacitor in the 10pF range is used to produce a high frequency pole that rolls off the loop gain following the RHPZ. But, if this capacitance, C6 on the EVM, is sized such that $\text{ESR} \times C_2 \neq R_3 \times C_6$, assuming $C_6 << C_3$, then the ESR zero's effect will be nullified and the design method in this application note is still applicable. In rare cases, $f_{ZESR}$ might be low enough in frequency to cancel $f_{P2}$ and eliminate the need for R3 and C3. In all cases, a 0.1μF-10μF ceramic output capacitor in parallel with the large high ESR output capacitor is recommended to reduce the output ripple.

He(s) models the inductor current sampling effect as well as the slope compensation ($S_E$) effect on the small signal response.

$$He(s) = \frac{1}{s \times \left[ \frac{1 + S_E}{S_N} \right] \times (1 - D) - 0.5} + \frac{s^2}{1 + \left( \frac{\pi \times f_{SW}}{f_{SW}} \right)^2}$$  \hspace{1cm} (9)

Where the natural and externally added slopes are...
With $R_{\text{OUT}} = 24\text{ V}/0.300\text{ A} = 80\ \Omega$ and $R_{\text{SENSE}} = 200\ \text{m\Omega}$, Figure 2 shows the Mathcad™ gain and phase of the power stage, $G_{\text{PW}}(s)$, with $s = j \times 2 \times \pi \times f$.

![Figure 3: Power Stage Gain and Phase](image)

To prevent switching noise or gain fluctuations due to changes in nonmeasured parameters from causing small signal instability, conventional wisdom recommends that the crossover frequency, $f_{\text{BW}}$, be kept below the lower $f_{\text{S(MIN)}}/5 = 200\ \text{kHz}$ or $f_{\text{RHPZ}}/3 = 45.3\ \text{kHz}$. In section 6, the designer chose $f_{\text{BW}} = 30\ \text{kHz}$. Therefore, the compensation gain, $K_{\text{COMP}}$, and power stage gain at the crossover frequency must be zero, or $K_{\text{COMP}}(f_{\text{BW}}) + 20\log(G_{\text{PW}}(f_{\text{BW}})) = 0$, so $K_{\text{COMP}}(f_{\text{BW}}) = -20\log(G_{\text{PW}}(f_{\text{BW}})) = -8\ \text{dB}$ as illustrated by the orange dashed line in Figure 2. Using Type II compensation and finding $G_{\text{EAmax}} = 400\ \mu\text{mho}$ in the data sheet, Equation 12 computes the value of $R3$ to give $K_{\text{COMP}}(f_{\text{BW}}) = -15\ \text{dB}$, rounded up to the closest standard value.

$$R3 \approx \frac{K_{\text{COMP}}(f_{\infty})}{10^{20\text{dB}}} = \frac{G_{\text{EA}} \times \frac{10^{9.5\ \text{dB}}}{10^{20\text{dB}}}}{1.05\ \text{kHz}} \times \frac{17.3 \text{ k\Omega}}{196 \text{ k\Omega} + 10.5 \text{ k\Omega}} \approx 17.4 \text{k\Omega}$$

From Equation 7, the designer set $f_{\infty} = f_{\text{BW}}/10 = 3\ \text{kHz}$ for maximum phase boost at the crossover point and solved for $C3$. The answer was rounded down to the closest standard value.

$$C3 \approx \frac{1}{2\pi \times R3 \times f_{\infty}} = \frac{1}{2\pi \times 17.4 \text{ k\Omega} \times 3 \text{ kHz}} \approx 3.04\ \text{nF} \rightarrow 2700\ \text{pF}$$

Figure 4 shows the Mathcad™ plot of $T(s) = G_{\text{PW}}(s) \times H_{\text{EA}}(s)$.
Figure 4. Total Loop Gain and Phase With \( R_3 = 17.4 \, \text{k} \Omega \) and \( C_3 = 2700 \, \text{pF} \)

Figure 5 shows the loop gain and phase as measured on a Venable Gain Phase Analyzer. The measured \( f_{BW} \) is closer to 40 kHz, slightly higher than the designed and simulated 30 kHz. The phase margin is slightly above 60° as expected.

Figure 5. Measured Loop Gain and Phase

Figure 6 shows the transient response for a 250-mA load step. The \( \Delta V_{\text{TRAN}} \) droop of 400 mV is well below the 500 mV specification. This performance is not unexpected due to the over-sized output capacitance and wider than designed loop bandwidth.
Figure 6. Load Transient Response

Figure 7 shows the efficiency.

![Efficiency Graph](https://www.ti.com/lit/an/slua319/slua319bd.pdf)

**Figure 7. Efficiency**

V\(_i\) = 12 V

Figure 8 shows the load regulation, which is well within the 1% specification.
Figure 8. Load Regulation

Figure 9 shows typical operating waveforms.

Figure 9. Operation Including $V_{\text{RIPPLE}}$ at $V_{\text{IN}} = 12$ V and $I_{\text{OUT}} = 200$ mA
The preceding design steps are applicable to any current-mode, control-based boost converter.
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