The TL431 in the Control of Switching Power Supplies
Agenda

- Feedback generalities
- The TL431 in a compensator
- Small-signal analysis of the return chain
- A type 1 implementation with the TL431
- A type 2 implementation with the TL431
- A type 3 implementation with the TL431
- Design examples
- Conclusion
Agenda

- Feedback generalities
- The TL431 in a compensator
- Small-signal analysis of the return chain
- A type 1 implementation with the TL431
- A type 2 implementation with the TL431
- A type 3 implementation with the TL431
- Design examples
- Conclusion
What is a Regulated Power Supply?

- $V_{out}$ is permanently compared to a reference voltage $V_{ref}$.
- The reference voltage $V_{ref}$ is precise and stable over temperature.
- The error, $\varepsilon = V_{ref} - \alpha V_{out}$, is amplified and sent to the control input.
- The power stage reacts to reduce $\varepsilon$ as much as it can.
How is Regulation Performed?

- Text books only describe op amps in compensators...

- The market reality is different: the TL431 rules!

I'm the law!

TL431

optocoupler
How do we Stabilize a Converter?

- We need a high gain at dc for a low static error
- We want a sufficiently high crossover frequency for response speed
- Shape the compensator $G(s)$ to build phase and gain margins!

<table>
<thead>
<tr>
<th>$T(s)$</th>
<th>$\angle T(s)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>T(s)</td>
</tr>
<tr>
<td>$0^\circ$</td>
<td>$-180^\circ$</td>
</tr>
<tr>
<td>$-0\text{ dB}$</td>
<td>$-88^\circ$</td>
</tr>
<tr>
<td>$f_c = 6.5 \text{ kHz}$</td>
<td></td>
</tr>
<tr>
<td>$\phi_m = 92^\circ$</td>
<td></td>
</tr>
<tr>
<td>$GM = 67 \text{ dB}$</td>
<td></td>
</tr>
</tbody>
</table>

$|T(s)| = -67 \text{ dB}$
How Much Phase Margin to Choose?

- a $Q$ factor of 0.5 (critical response) implies a $\varphi_m$ of 76°
- a 45° $\varphi_m$ corresponds to a $Q$ of 1.2: oscillatory response!

- phase margin depends on the needed response: fast, no overshoot…
- good practice is to shoot for 60° and make sure $\varphi_m$ always > 45°
Which Crossover Frequency to Select?

- crossover frequency selection depends on several factors:
  - switching frequency: theoretical limit is $F_{sw}/2$
  - in practice, stay below 1/5 of $F_{sw}$ for noise concerns
  - output ripple: if ripple pollutes feedback, «tail chasing» can occur.
  - crossover frequency rolloff is mandatory, e.g. in PFC circuits
  - presence of a Right-Half Plane Zero (RHPZ):
    - you cannot cross over beyond 30% of the lowest RHPZ position
  - output undershoot specification:
    - select crossover frequency based on undershoot specs

\[ V_p \approx \frac{\Delta I_{out}}{2\pi f_c C_{out}} \]
What Compensator Types do we Need?

- There are basically 3 compensator types:
  - type 1, 1 pole at the origin, no phase boost
  - type 2, 1 pole at the origin, 1 zero, 1 pole. Phase boost up to 90°
  - type 3, 1 pole at the origin, 1 zero pair, 1 pole pair. Boost up to 180°

Type 1

\[ |G(s)| \]
\[ \angle G(s) = -270° \]

Type 2

\[ |G(s)| \]
\[ \angle G(s) \]

Type 3

\[ |G(s)| \]
\[ \angle G(s) \]
Agenda

- Feedback generalities
- **The TL431 in a compensator**
- Small-signal analysis of the return chain
- A type 1 implementation with the TL431
- A type 2 implementation with the TL431
- A type 3 implementation with the TL431
- Design examples
- Conclusion
The TL431 Programmable Zener

- The TL431 is the most popular choice in nowadays designs
- It associates an open-collector op amp and a reference voltage
- The internal circuitry is self-supplied from the cathode current
- When the R node exceeds 2.5 V, it sinks current from its cathode

- The TL431 is a shunt regulator
The TL431 Programmable Zener

- The TL431 lends itself very well to optocoupler control

- $R_{LED}$ must leave enough headroom over the TL431: upper limit!
The TL431 Programmable Zener

- This LED resistor is a design limiting factor in low output voltages:

\[
R_{LED,\text{max}} \leq \frac{V_{out} - V_f - V_{TL431,\text{min}}}{V_{dd} - V_{CE,\text{sat}} + I_{bias \, \text{CTR}_{\text{min}}} R_{\text{pullup}}} \cdot R_{\text{pullup}} \cdot \text{CTR}_{\text{min}}
\]

- When the capacitor \( C_1 \) is a short-circuit, \( R_{LED} \) fixes the fast lane gain

\[
V_{FB}(s) = -\text{CTR} \cdot R_{\text{pullup}} \cdot I_1
\]

\[
I_1 = \frac{V_{out}(s)}{R_{LED}}
\]

\[
\frac{V_{FB}(s)}{V_{out}(s)} = -\text{CTR} \cdot \frac{R_{\text{pullup}}}{R_{LED}}
\]

This resistor plays a role in dc too!
The TL431 – the Static Gain Limit

Let us assume the following design:

\[ V_{out} = 5 \, V \]
\[ V_f = 1 \, V \]
\[ V_{TL431,\min} = 2.5 \, V \]
\[ V_{dd} = 4.8 \, V \]
\[ V_{CE,sat} = 300 \, mV \]
\[ I_{bias} = 1 \, mA \]
\[ CTR_{\min} = 0.3 \]
\[ R_{pullup} = 20 \, k\Omega \]

\[ R_{LED,max} \leq \frac{5 - 1 - 2.5}{4.8 - 0.3 + 1m \times 0.3 \times 20k} \times 20k \times 0.3 \]

\[ R_{LED,max} \leq 857 \, \Omega \]

In designs where \( R_{LED} \) fixes the gain, \( G_0 \) cannot be below 17 dB

\[ G_0 > CTR \frac{R_{pullup}}{R_{LED}} > 0.3 \frac{20}{0.857} > 7 \text{ or } \approx 17 \, dB \]

You cannot “amplify” by less than 17 dB
The TL431 – the Static Gain Limit

- You must identify the areas where compensation is possible

---

**Diagram Description:**

- **Not ok** region requires less than 17 dB of gain.
- **Ok** region requires 17 dB or more.
- **Frequency** $f_c > 500 \text{ Hz}$
A TL431 must be biased above 1 mA to guaranty its parameters. If not, its open-loop suffers – a 10-dB difference can be observed!

\[ I_{bias} = 1.3 \text{ mA} \]

\[ I_{bias} = 300 \mu\text{A} \]

Easy solution:

\[ R_{bias} = \frac{1}{1\text{ m}} = 1 \text{ k} \Omega \]
Agenda

- Feedback generalities
- The TL431 in a compensator
- **Small-signal analysis of the return chain**
  - A type 1 implementation with the TL431
  - A type 2 implementation with the TL431
  - A type 3 implementation with the TL431
- Design examples
- Conclusion
The TL431 is an open-collector op amp with a reference voltage. Neglecting the LED dynamic resistance, we have:

\[
I_1(s) = \frac{V_{out}(s) - V_{op}(s)}{R_{LED}}
\]

\[
V_{op}(s) = -V_{out}(s) \frac{sC_1}{R_{upper}} = -V_{out}(s) \frac{1}{sR_{upper}C_1}
\]

\[
I_1(s) = V_{out}(s) \frac{1}{R_{LED}} \left[ 1 + \frac{1}{sR_{upper}C_1} \right]
\]

We know that:

\[
V_{FB}(s) = -CTR \cdot R_{pullup} \cdot I_1
\]

\[
\frac{V_{FB}(s)}{V_{out}(s)} = \frac{R_{pullup} \cdot CTR}{R_{LED}} \left[ 1 + \frac{sR_{upper}C_1}{sR_{upper}C_1} \right]
\]
TL431 – Small-Signal Analysis

- In the previous equation we have:
  - a static gain \( G_0 = \text{CTR} \frac{R_{\text{pullup}}}{R_{\text{LED}}} \)
  - a 0-dB origin pole frequency \( \omega_{po} = \frac{1}{C_1 R_{\text{upper}}} \)
  - a zero \( \omega_z = \frac{1}{R_{\text{upper}} C_1} \)

- We are missing a pole for the type 2!

\[
V_{FB}(s) = \frac{R_{\text{pullup}} \text{CTR}}{R_{\text{LED}}} \left[ \frac{1 + s R_{\text{upper}} C_1}{s R_{\text{upper}} C_1 (1 + s R_{\text{pullup}} C_2)} \right]
\]
The optocoupler also features a parasitic capacitor, which comes in parallel with $C_2$ and must be accounted for.

\[ C_2 = C \parallel C_{opto} \]
The optocoupler must be characterized to know where its pole is located. Adjust $V_{bias}$ to have $V_{FB}$ at 2-3 V to be in the linear region, then perform an ac sweep. The pole in this example is found at 4 kHz. Another design constraint is given by:

$$C_{opto} = \frac{1}{2\pi R_{pullup} f_{pole}} = \frac{1}{6.28 \times 20k \times 4k} \approx 2 \, nF$$
Agenda

- Feedback generalities
- The TL431 in a compensator
- Small-signal analysis of the return chain
- A type 1 implementation with the TL431
- A type 2 implementation with the TL431
- A type 3 implementation with the TL431
- Design examples
- Conclusion
The TL431 in a Type 1 Compensator

- To make a type 1 (origin pole only) neutralize the zero and the pole

\[
\frac{V_{FB}(s)}{V_{out}(s)} = -\frac{R_{pullup}}{R_{LED}} \left[ \frac{1+sR_{upper}C_1}{sR_{upper}C_1(1+sR_{pullup}C_2)} \right]
\]

\[sR_{upper}C_1 = sR_{pullup}C_2\]

\[C_1 = \frac{R_{pullup}}{R_{upper}}C_2\]

\[\omega_{po} = \frac{1}{R_{upper}R_{LED}C_1}\]

- Once neutralized, you are left with an integrator

\[G(s) = \frac{1}{s\omega_{po}}\]

\[|G(f_c)| = \frac{f_{po}}{f_c}\]

\[f_{po} = G_{f_c}f_c\]

\[C_2 = \frac{CTR}{2\pi G_{f_c}f_cR_{LED}}\]
We want a 5-dB gain at 5 kHz to stabilize the 5-V converter

\[
\begin{align*}
V_{\text{out}} &= 5 \, V \\
V_f &= 1 \, V \\
V_{\text{TL431, min}} &= 2.5 \, V \\
V_{dd} &= 4.8 \, V \\
V_{CE, \text{sat}} &= 300 \, mV \\
I_{\text{bias}} &= 1 \, mA \\
\text{CTR}_{\text{min}} &= 0.3 \\
R_{\text{pullup}} &= 20 \, k\Omega \\
G_{fe} &= \frac{5}{20} = 1.77 \\
f_c &= 10 \, kHz \\
\end{align*}
\]

Apply 15% margin

\[
R_{LED, \max} \leq 857 \, \Omega \quad \rightarrow \quad R_{LED} = 728 \, \Omega
\]

\[
\begin{align*}
C_2 &= \frac{\text{CTR}}{2\pi G_{fe} f_c R_{LED}} = \frac{0.3}{6.28 \times 1.77 \times 5 \times 728} \approx 7.4 \, nF \\
C_{\text{opto}} &= 2 \, nF \\
C &= 7.4n - 2n = 5.4 \, nF \\
C_1 &= \frac{R_{\text{pullup}}}{R_{\text{upper}}} C_2 \approx 14.7 \, nF
\end{align*}
\]
TL431 Type 1 Design Example

- SPICE can simulate the design – automate elements calculations...

Parameters:
- Vout = 5
- Vf = 1
- Vref = 2.5
- VCESat = 300m
- Vdd = 4.8
- Ibias = 1m

\[ A = Vout - Vf - Vref \]
\[ B = Vdd - VCESat + Ibias \times CTR \times R_{pullup} \]
\[ R_{pullup} = (Vout - 2.5) / 250u \]
\[ f_c = 5k \]
\[ G_{fc} = 5 \]

\[ G = 10^{(-G_{fc}/20)} \]
\[ \pi = 3.14159 \]

\[ F_{po} = G \times f_c \]
\[ R_{pullup} = 20k \]

\[ R_{LED} = R_{max} \times 0.85 \]
\[ C_1 = C_{pole1} \times R_{pullup} / R_{upper} \]

\[ C_{pole1} = CTR / (2 \times \pi \times F_{po} \times R_{LED}) \]
\[ C_{pole} = C_{pole1} - C_{opto} \]

\[ F_{opto} = 4k \]
\[ C_{opto} = 1 / (2 \times \pi \times F_{opto} \times R_{pullup}) \]

\[ CTR = 0.3 \]
We have a type 1 but 1.3 dB of gain is missing?

$$|G(s)|$$

3.7 dB

$$\arg G(s)$$

90.0

Hu?
TL431 Type 1 Design Example

- The 1-kΩ resistor in parallel with the LED is an easy bias.
- However, as it appears in the loop, does it affect the gain?

\[
\begin{align*}
V_{FB}(s) &= I_c R_{pullup} = I_L R_{pullup} \text{CTR} \\
I_L &= I_1 \frac{R_{bias}}{R_{bias} + R_d} \\
I_L &= \frac{V_{out}}{R_{LED} + R_{bias} \parallel R_d} \frac{R_{bias}}{R_{bias} + R_d} \\
V_{FB} \bigg|_{s=0} &= \frac{R_{pullup} \text{CTR}}{R_{LED} + R_{bias} \parallel R_d} \frac{R_{bias}}{R_{bias} + R_d}
\end{align*}
\]

- Both bias and dynamic resistances have a role in the gain expression.
TL431 Type 1 Design Example

- A low operating current increases the dynamic resistor

SFH615A-2 -FORWARD CHARACTERISTICS

- Make sure you have enough LED current to reduce its resistance

\[ R_{\text{pullup}} = 20 \, \text{k}\Omega, \, I_F = 300 \, \mu\text{A} \, (\text{CTR} = 0.3) \]
\[ R_d = 158 \, \Omega \]

\[ R_{\text{pullup}} = 1 \, \text{k}\Omega, \, I_F = 1 \, \text{mA} \, (\text{CTR} = 1) \]
\[ R_d = 38 \, \Omega \]
The pullup resistor is 1 kΩ and the target now reaches 5 dB
Agenda

- Feedback generalities
- The TL431 in a compensator
- Small-signal analysis of the return chain
- A type 1 implementation with the TL431
- A type 2 implementation with the TL431
- A type 3 implementation with the TL431
- Design examples
- Conclusion
The TL431 in a Type 2 Compensator

- Our first equation was already a type 2 definition, we are all set!

\[ G_0 = \text{CTR} \frac{R_{\text{pullup}}}{R_{\text{LED}}} \]

\[ \omega_{z_1} = \frac{1}{R_{\text{upper}} C_1} \]

\[ \omega_{p_1} = \frac{1}{R_{\text{pullup}} C_2} \]

- Just make sure the optocoupler contribution is involved…
TL431 Type 2 Design Example

- You need to provide a 15-dB gain at 5 kHz with a 50° boost

\[
f_p = \left[ \tan(\text{boost}) + \sqrt{\tan^2(\text{boost}) + 1} \right]
f_c = 2.74 \times 5k = 13.7 \text{ kHz}
\]

\[
f_z = \frac{f_c^2}{f_p} = \frac{25k}{13.7k} \approx 1.8 \text{ kHz}
\]

\[G_0 = \text{CTR} \frac{R_{\text{pullup}}}{R_{\text{LED}}} = 10^{15/20} = 5.62\]

- With a 250-µA bridge current, the divider resistor is made of:

\[R_{\text{lower}} = \frac{2.5}{250u} = 10 \text{ kΩ}
\]

\[R_1 = \left(12 - 2.5\right)/250u = 38 \text{ kΩ}\]

- The pole and zero respectively depend on \(R_{\text{pullup}}\) and \(R_1\):

\[C_2 = \frac{1}{2\pi f_p R_{\text{pullup}}} = 581 \text{ pF}\]

\[C_1 = \frac{1}{2\pi f_z R_1} = 2.3 \text{ nF}\]

- The LED resistor depends on the needed mid-band gain:

\[R_{\text{LED}} = \frac{R_{\text{pullup}} \text{CTR}}{G_0} = 1.06 \text{ kΩ}\]

\[\text{ok} \quad R_{\text{LED,max}} \leq 4.85 \text{ kΩ}\]
TL431 Type 2 Design Example

- The optocoupler is still at a 4-kHz frequency:
  \[ C_{pole} \approx 2 \text{nF} \quad \text{Already above!} \]
- Type 2 pole capacitor calculation requires a 581 pF cap.!

  The bandwidth cannot be reached, reduce \( f_c \)!

- For noise purposes, we want a minimum of 100 pF for \( C \)
- With a total capacitance of 2.1 nF, the highest pole can be:
  \[
  f_{\text{pole}} = \frac{1}{2\pi R_{\text{pullup}} C} = \frac{1}{6.28 \times 20 \text{k} \times 2.1 \text{n}} = 3.8 \text{kHz}
  \]

- For a 50° phase boost and a 3.8-kHz pole, the crossover must be:
  \[
  f_c = \frac{f_p}{\tan(\text{boost}) + \sqrt{\tan^2(\text{boost}) + 1}} \approx 1.4 \text{kHz}
  \]
The zero is then simply obtained:

\[ f_z = \frac{f_c^2}{f_p} = 516 \text{ Hz} \]

We can re-derive the component values and check they are ok

\[ C_2 = \frac{1}{2\pi f_p R_{\text{pullup}}} = 2.1 \text{ nF} \quad C_1 = \frac{1}{2\pi f_z R_1} = 8.1 \text{ nF} \]

Given the 2-nF optocoupler capacitor, we just add 100 pF

In this example, \( R_{\text{LED,max}} \) is 4.85 kΩ

\[ G_0 > \text{CTR} \frac{R_{\text{pullup}}}{R_{\text{LED}}} > 0.3 \frac{20}{4.85} > 1.2 \text{ or } \approx 1.8 \text{ dB} \]

You cannot use this type 2 if an attenuation is required at \( f_c \)!
The 1-dB gain difference is linked to $R_d$ and the bias current.
The gain limit problem comes from the fast lane presence. Its connection to $V_{out}$ creates a parallel input. The solution is to hook the LED resistor to a fixed bias.
TL431 – Suppressing the Fast Lane

The equivalent schematic becomes an open-collector op amp.
TL431 – Suppressing the Fast Lane

- The small-signal ac representation puts all sources to 0

\[ O(s) = \frac{R_{pullup}}{R_{LED}} CTR \frac{1}{1 + sR_{pullup}C_{pole}} \]

\[ G(s) \]

\[ G_1(s) = \frac{1 + R_2C_1}{sR_1C_1} \]
TL431 – Suppressing the Fast Lane

- The op amp can now be wired in any configuration!
- Just keep in mind the optocoupler transmission chain

\[
O(s) = \frac{R_{\text{pullup}}}{R_{\text{LED}}} \cdot \text{CTR} \cdot \frac{1}{1 + sR_{\text{pullup}}C_{\text{pole}}}
\]

- Wire the op amp in type 2A version (no high frequency pole)

\[
G_1(s) = \frac{1 + R_2C_1}{sR_1C_1}
\]

- When cascaded, you obtain a type 2 with an extra gain term

\[
G(s) = \frac{R_{\text{pullup}}}{R_{\text{LED}}} \cdot \text{CTR} \cdot \frac{1 + R_2C_1}{sR_1C_1 \left(1 + sR_{\text{pullup}}C_{\text{pole}}\right)}
\]
TL431 Type 2 Design Example – No Fast Lane

- We still have a constraint on $R_{LED}$ but only for dc bias purposes

$$R_{LED,\text{max}} \leq \frac{V_z - V_f - V_{\text{TL431,min}}}{V_{\text{dd}} - V_{CE,\text{sat}} + I_{\text{bias}} \cdot \text{CTR}_{\text{min}} \cdot R_{\text{pullup}}} \cdot \frac{R_{\text{pullup}} \cdot \text{CTR}_{\text{min}}}{1}$$

- You need to attenuate by -10-dB at 1.4 kHz with a 50° boost
- The poles and zero position are that of the previous design

\[
\begin{align*}
V_z & = 6.2 \, V \\
V_f & = 1 \, V \\
V_{\text{TL431,min}} & = 2.5 \, V \\
V_{\text{dd}} & = 4.8 \, V \\
V_{CE,\text{sat}} & = 300 \, mV \\
I_{\text{bias}} & = 1 \, mA \\
\text{CTR}_{\text{min}} & = 0.3 \\
R_{\text{pullup}} & = 20 \, k\Omega
\end{align*}
\]

Apply 15% margin

$$R_{LED,\text{max}} \leq 1.5 \, k\Omega \quad \rightarrow \quad R_{LED} = 1.27 \, k\Omega$$

$$f_z = 516 \, Hz \quad f_p = 3.8 \, kHz$$
TL431 Type 2 Design Example – No Fast Lane

- We need to account for the extra gain term:
  \[ G_2 = \frac{R_{\text{pullup}}}{R_{\text{LED}}} \times \text{CTR} = \frac{20k}{1.27k} \times 0.3 = 4.72 \]

- The required total mid-band attenuation at 1.4 kHz is -10 dB
  \[ G_{f_c} = 10^{-10/20} = 0.316 \]

- The mid-band gain from the type 2A is therefore:
  \[ G_1 = \frac{G_0}{G_2} = \frac{0.316}{4.72} = 0.067 \text{ or } -23.5 \text{ dB} \]

- Calculate \( R_2 \) for this attenuation:
  \[ R_2 = G_1 R_1 \sqrt{\left(\frac{f_c}{f_p}\right)^2 + 1} \]

\[ \left(\frac{f_c}{f_c}\right)^2 + 1 = 2.6 \text{ k\Omega} \]
TL431 Type 2 Design Example – No Fast Lane

- An automated simulation helps to test the calculation results

Parameters

\[ V_{out} = 12 \]
\[ R_{upper} = \frac{(V_{out} - 2.5)}{250} \]
\[ f_c = 1.4 \]
\[ G_{fc} = 10 \]
\[ V_f = 1 \]
\[ I_{bias} = 1 \mu A \]
\[ V_{ref} = 2.5 \]
\[ V_{CEsat} = 300 \mu A \]
\[ V_{dd} = 5 \]

\[ V_{z} = 6.2 \]
\[ R_{pullup} = 20 \kOmega \]
\[ F_{opto} = 4 \kOmega \]
\[ C_{opto} = \frac{1}{(2 \pi R_{pullup} F_{opto})} \]
\[ C_{TR} = \frac{1}{(2 \pi F_{opto})} \]
\[ G_1 = R_{pullup} C_{TR} R_{upper} \]
\[ G_2 = 10^2 \cdot \frac{G_{fc}}{20} \]
\[ G = G_2 / G_1 \]
\[ \pi = 3.14159 \]
\[ f_z = 516 \]
\[ f_p = 3.8 \kOmega \]
\[ C_1 = 1 / (2 \pi f_z R_2) \]
\[ C_{pole2} = 1 / (2 \pi f_p R_{pullup}) \]
\[ C_2 = C_{pole2} - C_{opto} \]
\[ a = (f_z^2 + f_c^2) \cdot (f_p^2 + f_c^2) \]
\[ c = (f_z^2 + f_c^2) \]
\[ R_2 = \frac{\sqrt{a}}{c} \cdot G \cdot f_c \cdot R_{upper} / f_p \]
\[ R_{max1} = (V_z - V_f - V_{ref}) \]
\[ R_{max2} = (V_{dd} - V_{CEsat} + I_{bias} \cdot R_{pullup} \cdot C_{TR}) \]
\[ R_{LED} = (R_{max1} + R_{max2}) \cdot R_{pullup} \cdot C_{TR} \cdot 0.85 \]
The simulation results confirm the calculations are ok.

-10 dB @ 1.4 kHz

50°
Agenda

- Feedback generalities
- The TL431 in a compensator
- Small-signal analysis of the return chain
- A type 1 implementation with the TL431
- A type 2 implementation with the TL431
- A type 3 implementation with the TL431
- Design examples
- Conclusion
The TL431 in a Type 3 Compensator

- The type 3 with a TL431 is difficult to put in practice

- Suppress the fast lane for an easier implementation!

**Equations:**

\[ f_{z1} = \frac{1}{2\pi R_1 C_1} \]

\[ f_{z2} = \frac{1}{2\pi (R_{LED} + R_pz) C_pz} \]

\[ f_{p1} = \frac{1}{2\pi R_{pz} C_pz} \]

\[ f_{p2} = \frac{1}{2\pi R_{pullup} \left( C_2 || C_{opto} \right)} \]

\[ G = \frac{R_{pullup}}{R_{LED}} CTR \]

**Note:**

- \( R_{LED} \) fixes the gain and a zero position.
The TL431 in a Type 3 Compensator

Once the fast lane is removed, you have a classical configuration

\[
\begin{align*}
f_{z1} &= \frac{1}{2\pi R_2 C_1} \\
V_{zd} &= \frac{1}{2\pi R_1 C_3} \\
f_{p1} &= \frac{1}{2\pi R_3 C_3} \\
f_{p2} &= \frac{1}{2\pi R_{pullup} \left( \frac{C_2}{|| C_{opto} } \right)} \\
G &= \frac{R_{pullup}}{R_{LED}} \cdot CTR
\end{align*}
\]
We want to provide a 10-dB attenuation at 1 kHz
The phase boost needs to be of 120°
place the double pole at 3.7 kHz and the double zero at 268 Hz
Calculate the maximum LED resistor you can accept, apply margin

\[
R_{LED,max} \leq \frac{V_z - V_f - V_{TL431,min}}{V_{dd} - V_{CE,sat} + I_{bias} CTR_{min} R_{pullup}} R_{pullup} CTR_{min} \leq 1.5 \, k\Omega \times 0.85 \rightarrow 1.3 \, k\Omega
\]

We need to account for the extra gain term:

\[
G_2 = \frac{R_{pullup}}{R_{LED}} CTR = \frac{20k}{1.3k} 0.3 = 4.6
\]

The required total mid-band attenuation at 1 kHz is -10 dB

\[
G_{f_c} = 10^{-10/20} = 0.316
\]
TL431 Type 3 Design Example – No Fast Lane

- The mid-band gain from the type 3 is therefore:

\[ G_1 = \frac{G_0}{G_2} = \frac{0.316}{4.6} = 0.068 \text{ or } -23.3 \text{ dB} \]

- Calculate \( R_2 \) for this attenuation:

\[
R_2 = \frac{G_1 R_1 f_{p_1}}{f_{p_1} - f_{z_1}} \sqrt{1 + \left( \frac{f_c}{f_{p_1}} \right)^2} \sqrt{1 + \left( \frac{f_c}{f_{p_2}} \right)^2} = 744 \Omega
\]

\[ C_1 = 800 \text{ nF} \quad C_2 = 148 \text{ pF} \quad C_3 = 14.5 \text{ nF} \quad C_{opto} = 2 \text{ nF} \]

- The optocoupler pole limits the upper double pole position
- The maximum boost therefore depends on the crossover frequency
The decoupling between $V_{out}$ and $V_{bias}$ affects the curves.

-9.3 dB @ 1 kHz
-10 dB @ 1 kHz

Isolated 12-V dc source

135°
Agenda

- Feedback generalities
- The TL431 in a compensator
- Small-signal analysis of the return chain
- A type 1 implementation with the TL431
- A type 2 implementation with the TL431
- A type 3 implementation with the TL431
- **Design examples**
- Conclusion
Design Example 1 – a Single-Stage PFC

- The single-stage PFC is often used in LED applications
- It combines isolation, current-regulation and power factor correction
- Here, a constant on-time BCM controller, the **NCL30000**, is used

![Design Example 1 Diagram]

Parameters:

- V<sub>rms</sub>=100
- L=400µH

On-time selection:

- C<sub>r</sub>=1.5n
- I<sub>charge</sub>=270u
- G<sub>pwm</sub>=(C<sub>r</sub>/I<sub>charge</sub>)*1Meg

On-time selection equations:

- 1 V = 1 µs

Average simulation:

- I<sub>out</sub> = 2.4 A
- P=50 V
- 2 A string
Design Example 1 – a Single-Stage PFC

- Once the converter elements are known, ac-sweep the circuit
- Select a crossover low enough to reject the ripple, e.g. 20 Hz

![Graph showing the magnitude and phase of H(s)]
Design Example 1 – a Single-Stage PFC

- Given the low phase lag, a type 1 can be chosen.
- Use the type 2 with fast lane removal where $f_p$ and $f_z$ are coincident.
Design Example 1 – a Single-Stage PFC

- A transient simulation helps to test the system stability

\[ I_{LED}(t) \]

\[ V_{FB}(t) \]

\[ I_{in}(t) \]

\[ V_{in} = 100 \, V \text{ rms} \]
Design Example 2: a DCM Flyback Converter

- We want to stabilize a 20 W DCM adapter
- $V_{in} = 85$ to $265$ V rms, $V_{out} = 12$ V/1.7 A
- $F_{sw} = 65$ kHz, $R_{pullup} = 20$ kΩ
- Optocoupler is SFH-615A, pole is at 6 kHz
- Cross over target is 1 kHz
- Selected controller: NCP1216

1. Obtain a power stage open-loop Bode plot, $H(s)$
2. Look for gain and phase values at cross over
3. Compensate gain and build phase at cross over, $G(s)$
4. Run a loop gain analysis to check for margins, $T(s)$
5. Test transient responses in various conditions
Design Example 2: a DCM Flyback Converter

- Capture a SPICE schematic with an averaged model

- Look for the bias points values: \( V_{\text{out}} = 12 \text{ V}, \text{ ok} \)
Design Example 2: a DCM Flyback Converter

- Observe the open-loop Bode plot and select $f_c$: 1 kHz

**Magnitude at 1 kHz:**
-23 dB

**Phase at 1 kHz:**
-70°
Design Example 2: a DCM Flyback Converter

- Apply $k$ factor or other method, get $f_z$ and $f_p$
- $f_z = 3.5$ kHz $f_p = 4.5$ kHz

$\frac{k}{C_n} F = \frac{3.8}{20 \\text{k}\Omega}$

$C_n n F = \approx -2.5 \text{nF}$

$V_{dd}$

$20 \text{k}\Omega$

$V_{out}(s)$

$2 \text{k}\Omega$

$38 \text{k}\Omega$

$10 \text{nF}$

$k$ factor gave

$C = 3.8 \text{nF}$

install

$C_2 = 3.8n - 1.3n \approx 2.5 \text{nF}$

$2.5 \text{nF}$

$C_{opto} = 1.3 \text{nF}$

$10 \text{k}\Omega$
Design Example 2: a DCM Flyback Converter

- Check loop gain and watch phase margin at $f_c$

![Graph showing Bode plot with phase margin and crossover frequency](image)

- $\phi_m = 60^\circ$
- Crossover at 1 kHz
Design Example 2: a DCM Flyback Converter

- Sweep ESR values and check margins again

![Graph showing $V_{out}(t)$ with Hi and Low line markers.]

- Excellent!

200 mA to 2 A in 1 A/µs
Use an Automated Design Tool

- To speed-up your design studies, use the right tool!

1. Enter calculated values

2. Show power stage gain and phase

3. Compute pole/zero check open loop gain

4. See final values on TL431

www.onsemi.com
NCP1200, design tools
Conclusion

- Classical loop control theory describes op amps in compensators
- Engineers cannot apply their knowledge to the TL431
- Examples show that the TL431 with an optocoupler have limits
- Once these limits are understood, the TL431 is simple to use
- All three compensator types have been covered
- Design examples showed the power of averaged models
- Use them to extensively reproduce parameter dispersions
- Applying these recipes is key to design success!

Merci !
Theodore
Thank you!
Xiè-xie!
For More Information

• View the extensive portfolio of power management products from ON Semiconductor at www.onsemi.com

• View reference designs, design notes, and other material supporting the design of highly efficient power supplies at www.onsemi.com/powersupplies