ON Semiconductor®

Introduction to Loop Control with TL431

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Course Agenda

☐ Generalities on Control Systems

☐ Current Mode Control

☐ The TL431 in the Secondary Side

☐ Building a Type 2 Compensator

☐ A Design Example

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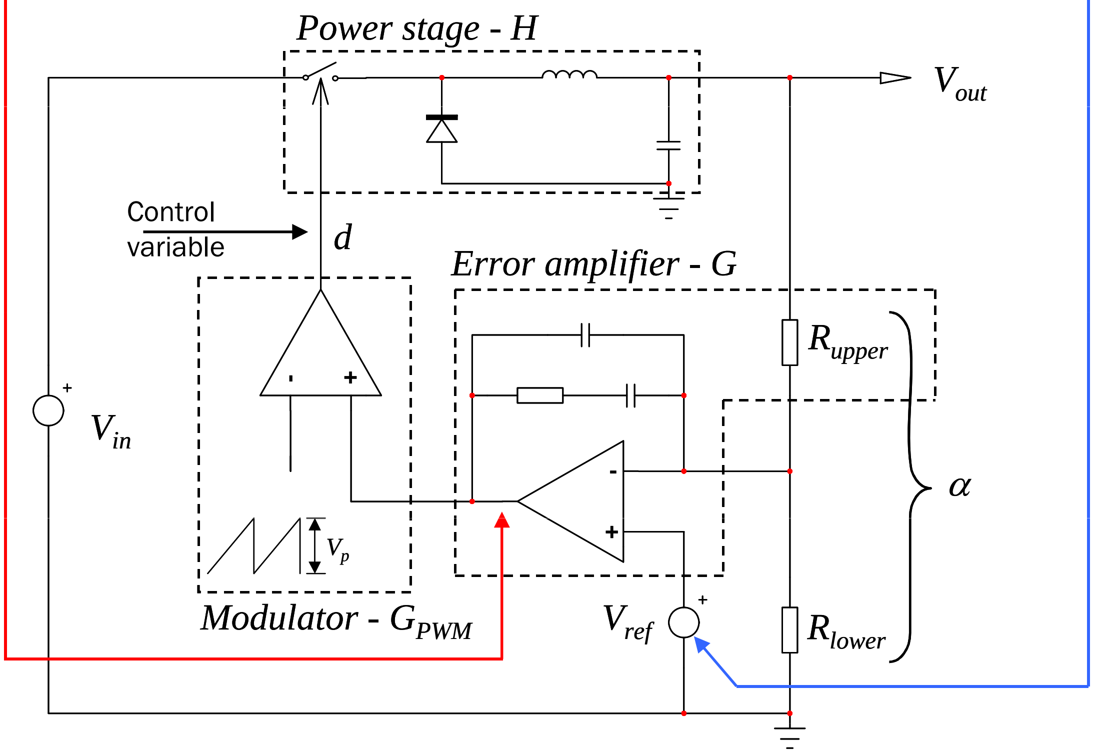
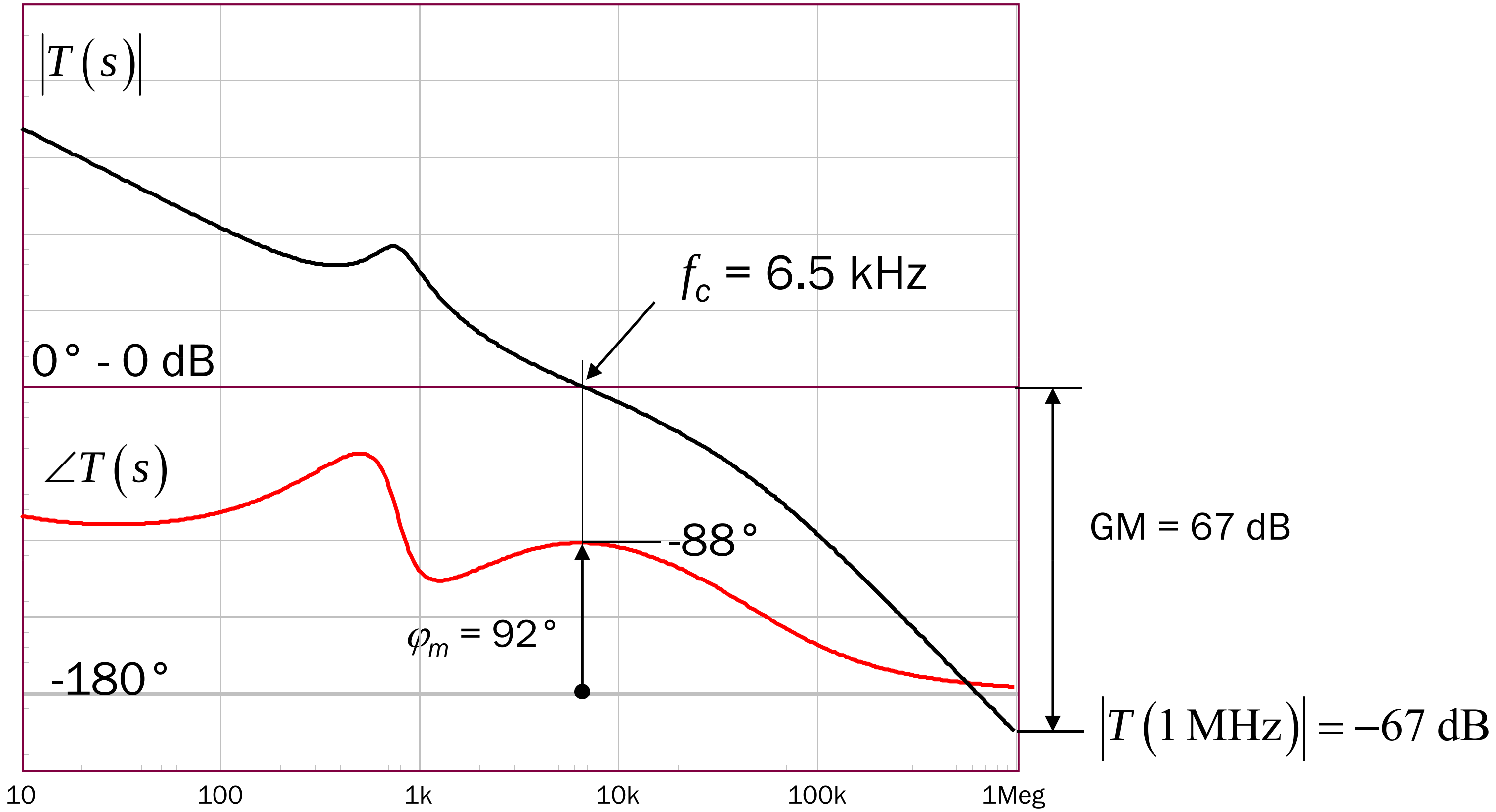
What is a Regulated Power Supply?

- V_{out} is permanently compared to a reference voltage V_{ref}.
- The V_{ref} voltage 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 ε as much as it can.



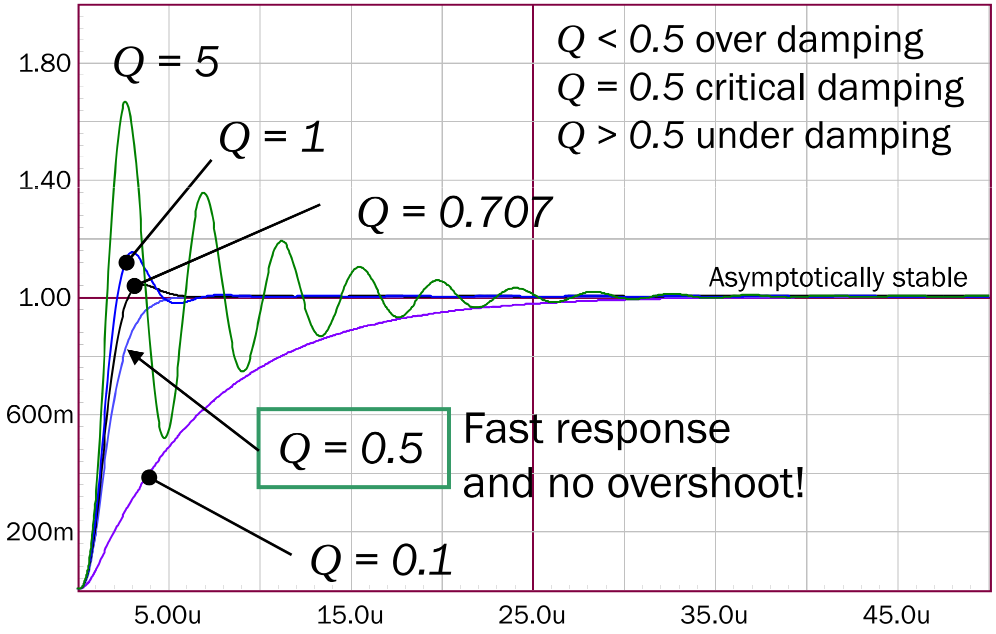
How do we Stabilize a Converter?

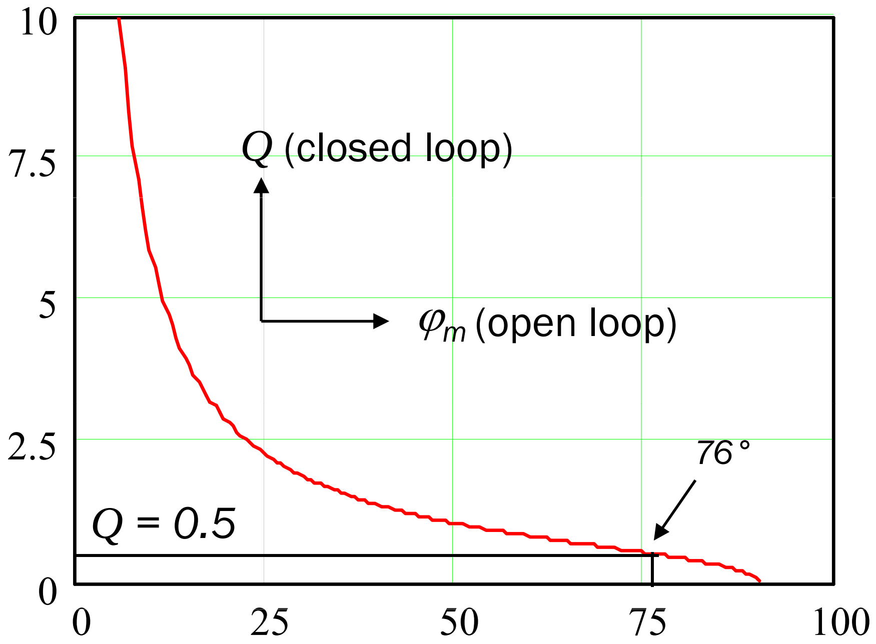
- ☐ We need a high dc gain for a low static error
- ☐ We want a high crossover frequency for response speed
- ➢ Shape the compensator $G(s)$ to build phase and gain margins!



How Much Margin do we Need?

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

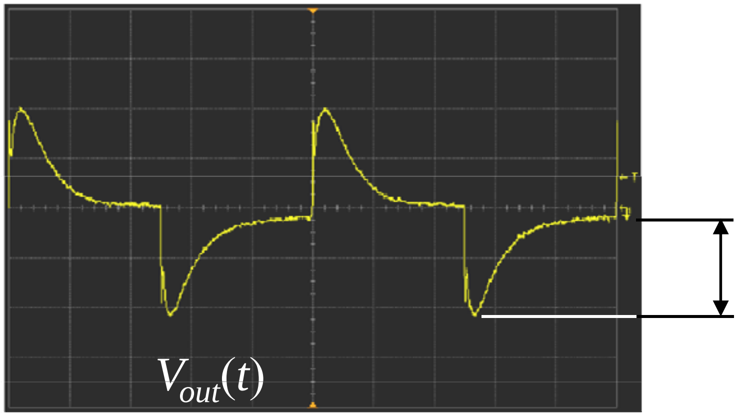




- phase margin depends on the response you want: fast, overshoot…
- good practice is to shoot for 60° and make sure φ_m always > 45°

What Crossover 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
  - ■ *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



$$V_p \approx \frac{\Delta I_{out}}{2\pi f_c C_{out}}$$

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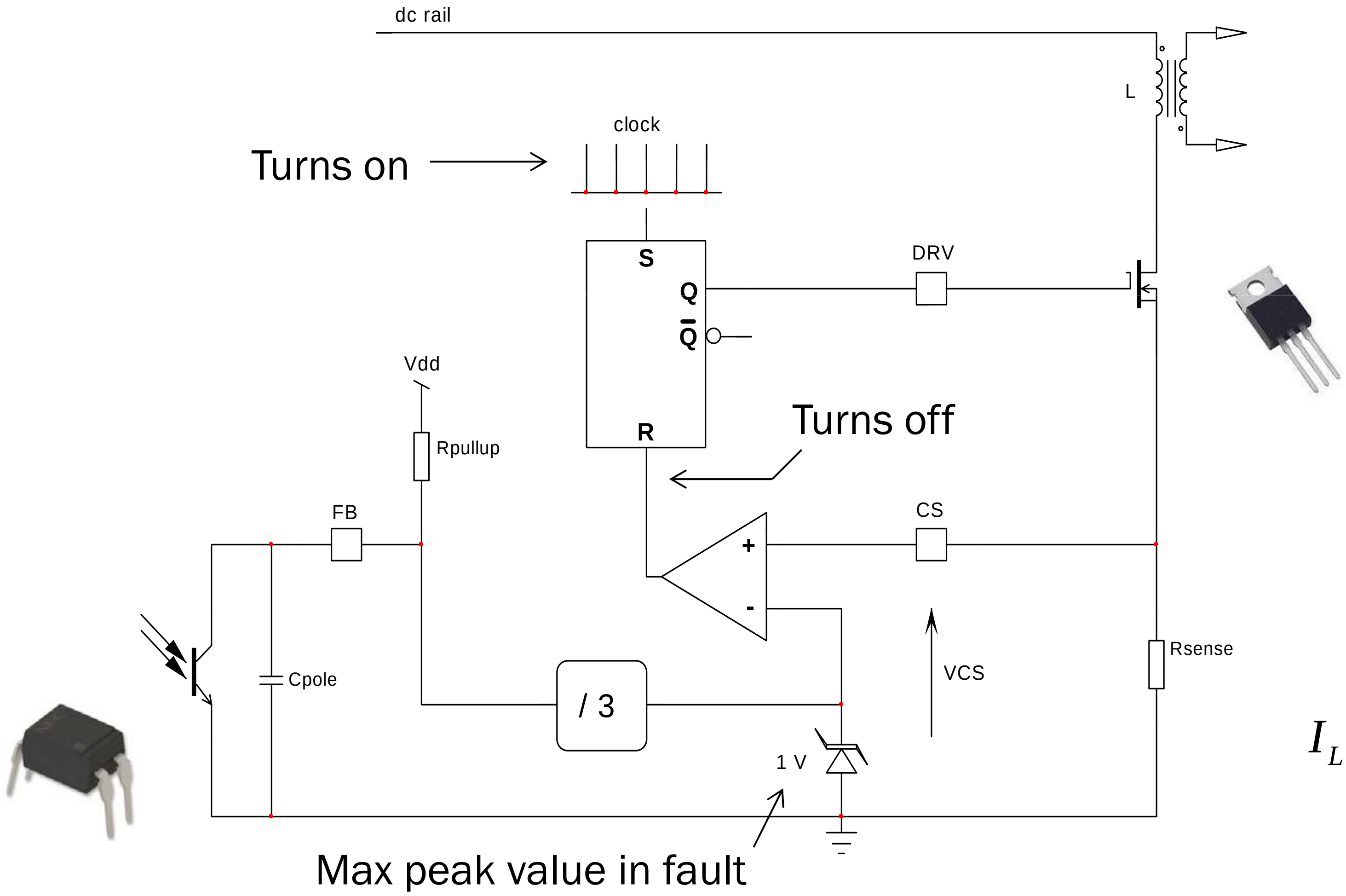
Peak Current Mode Control

- ☐ Clock initiates MOSFET turn-on, current comp. turns it off



Turns on

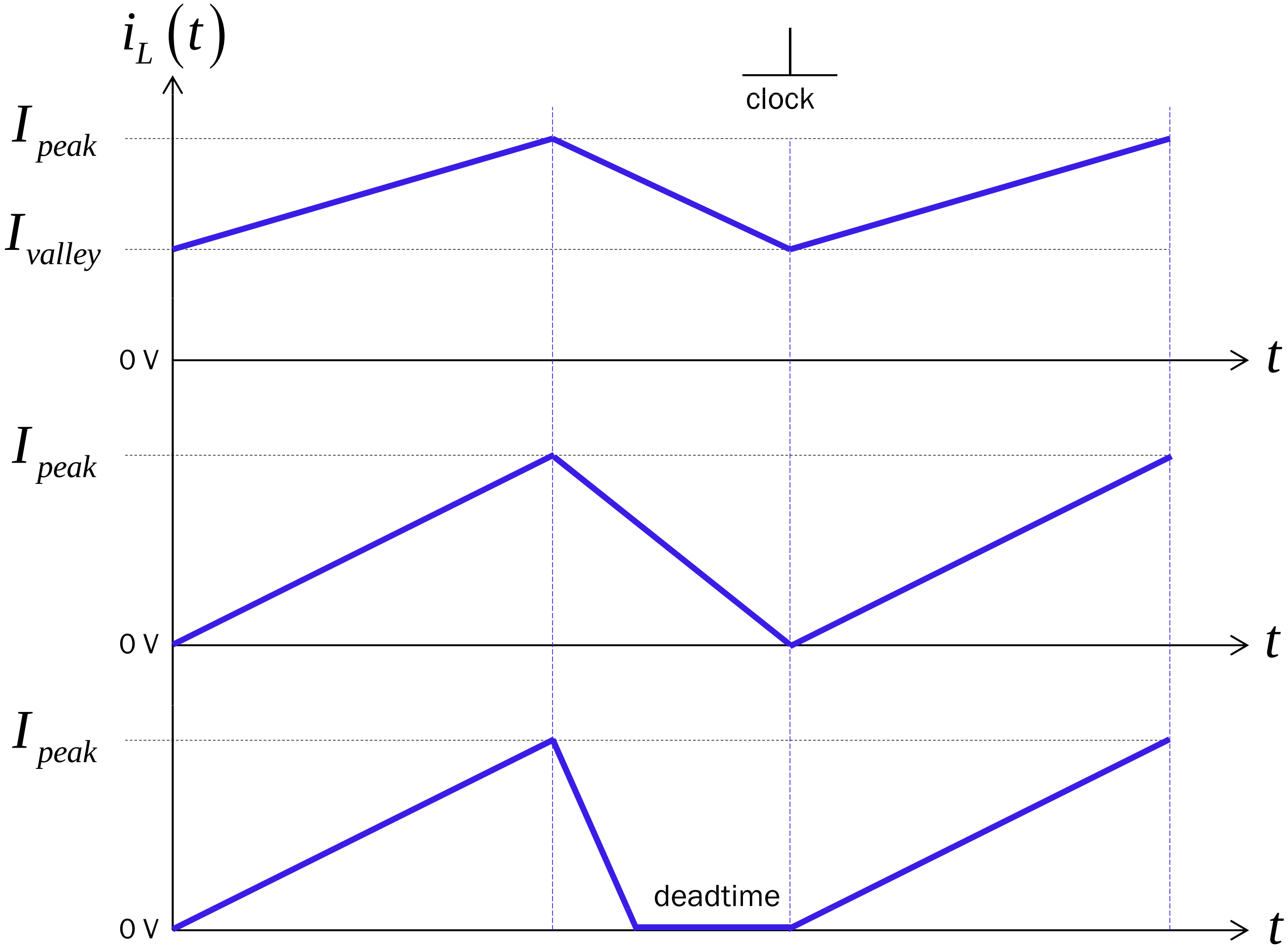
Turns off

Max peak value in fault

$$I_{L,peak} = \frac{V_{CS}}{R_{sense}}$$

Operating Modes

- ☐ The operating mode affects the converter dynamics



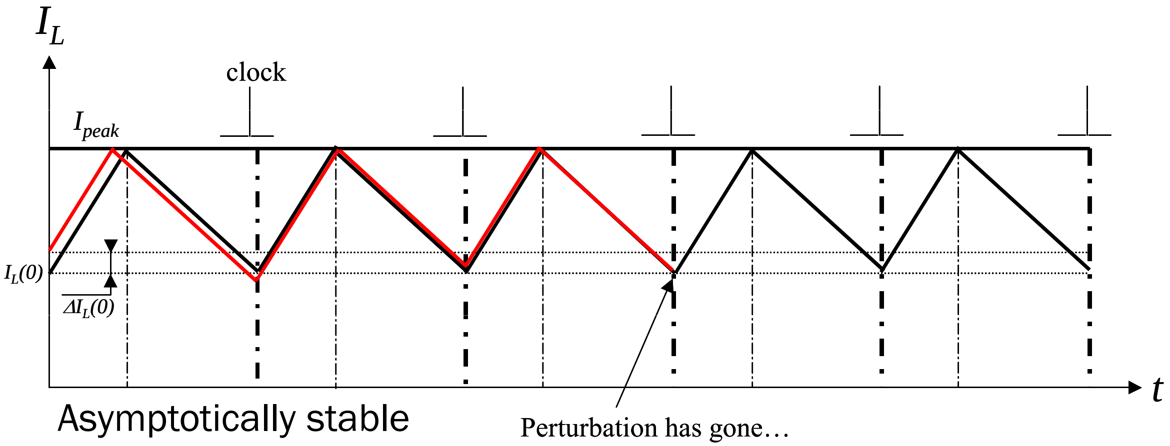
Continuous Conduction Mode (CCM)

Borderline Conduction Mode (BCM)

Discontinuous Conduction Mode (DCM)

Current Loop Instability in Current Mode

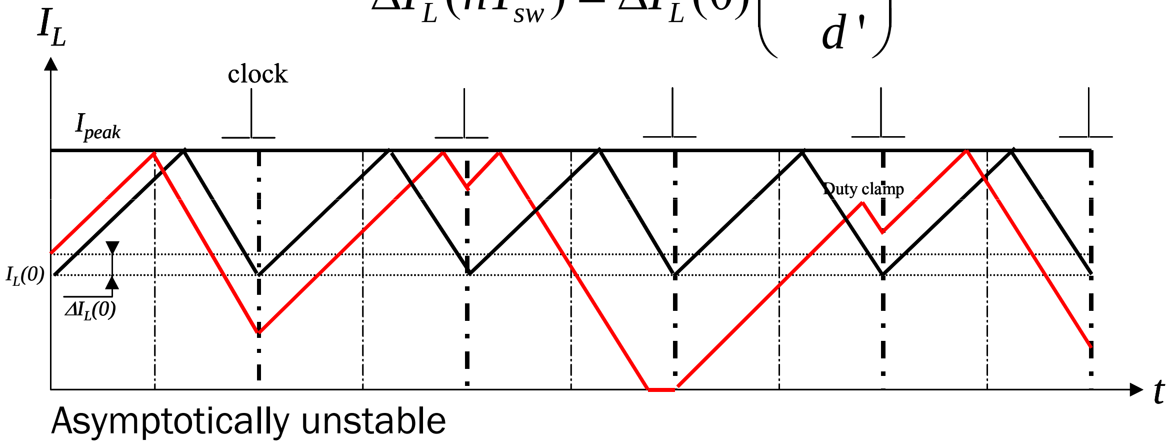
☐ Instabilities occur in Continuous Conduction Mode (CCM)



Asymptotically stable

duty ratio < 50%

$$\Delta I_L(nT_{sw}) = \Delta I_L(0)\left(-\frac{d}{d'}\right)^n$$

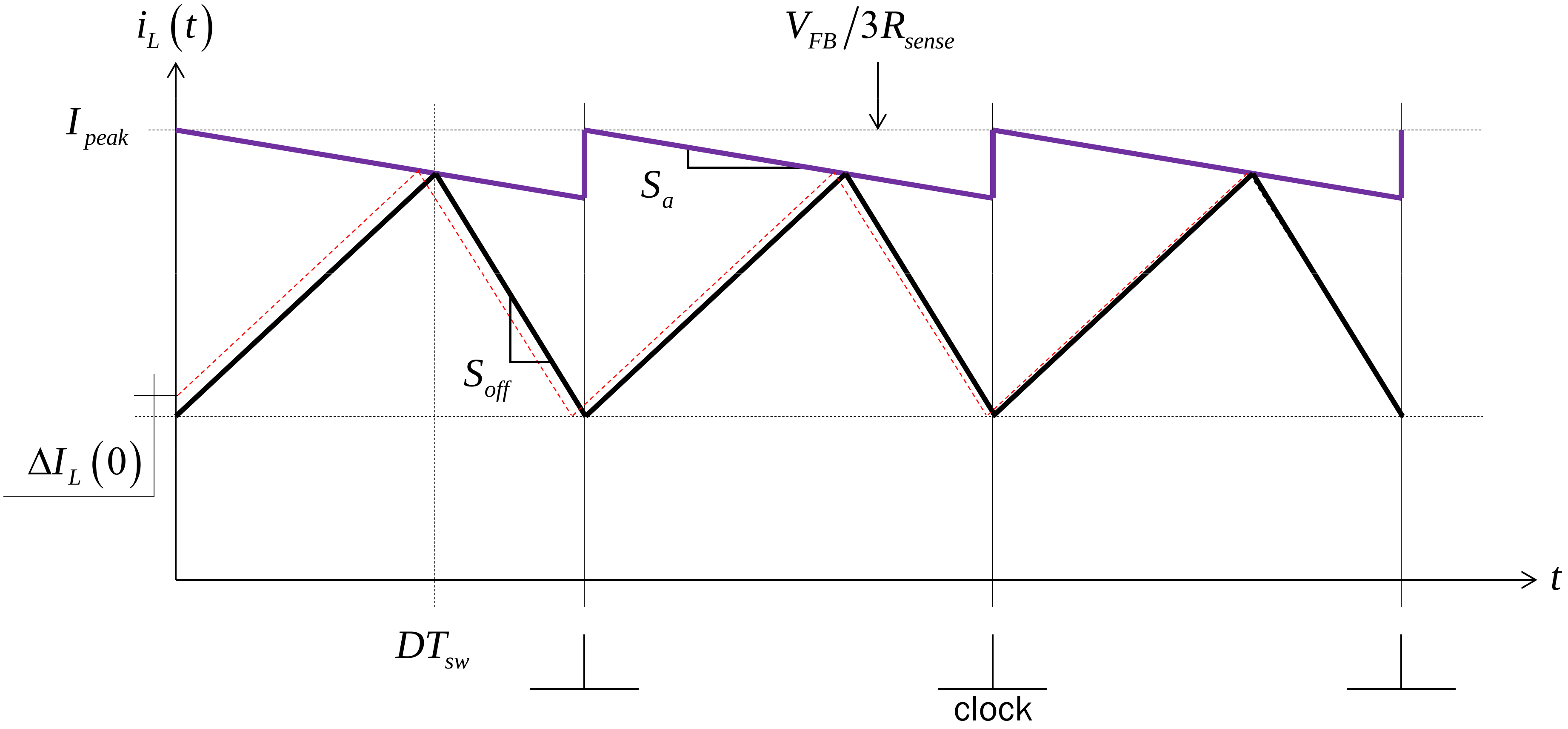


Asymptotically unstable

duty ratio > 50%

Slope Compensation Cures Instabilities

- ☐ An artificial ramp reduces the duty ratio and calms oscillations

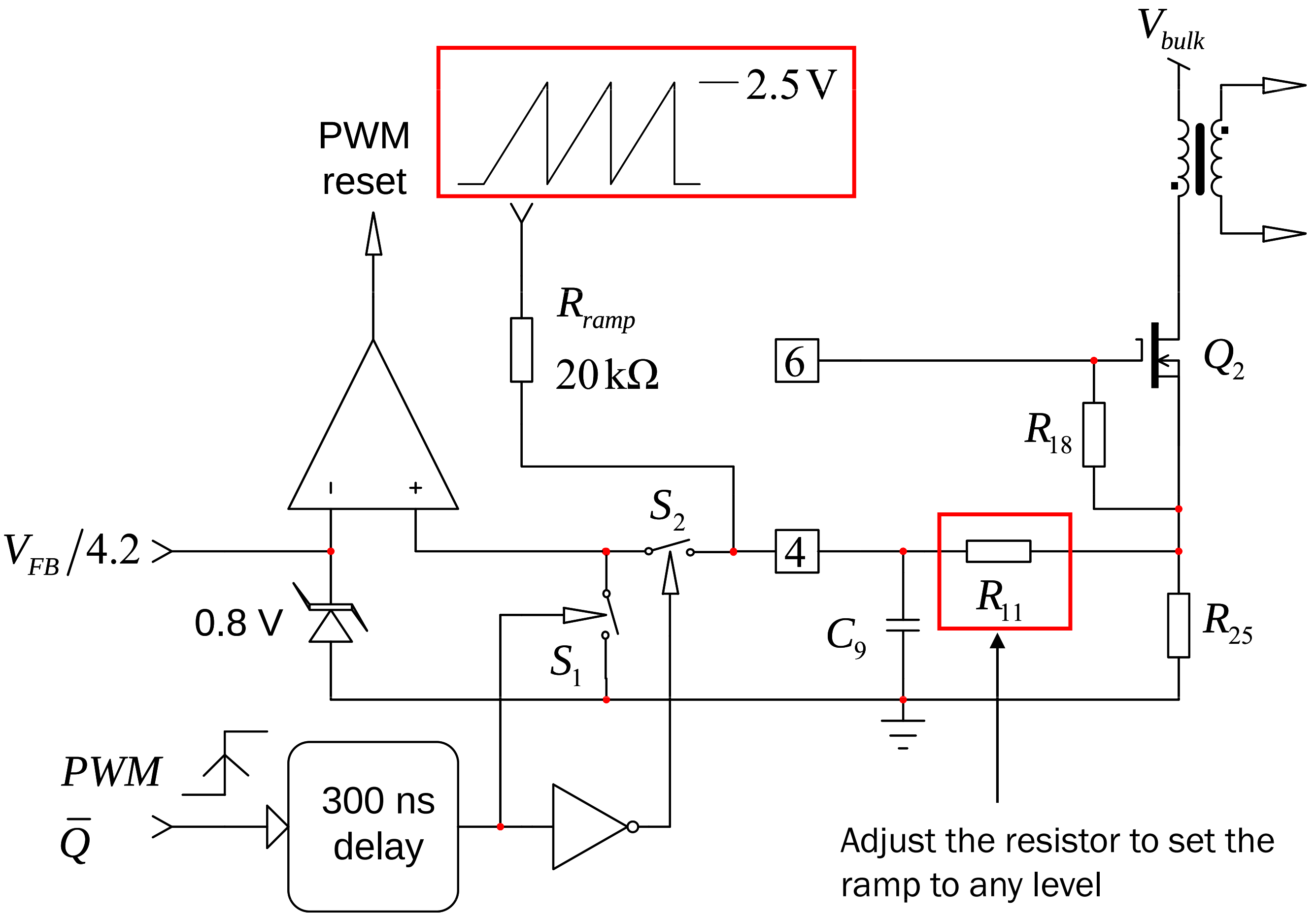


- ☐ Stability in ensured if $S_a > 50\% \cdot S_{off}$

For duty ratios up to 100%

A Simple Implementation in NCP1250

- ☐ A resistance in series with current sense resistor does the job

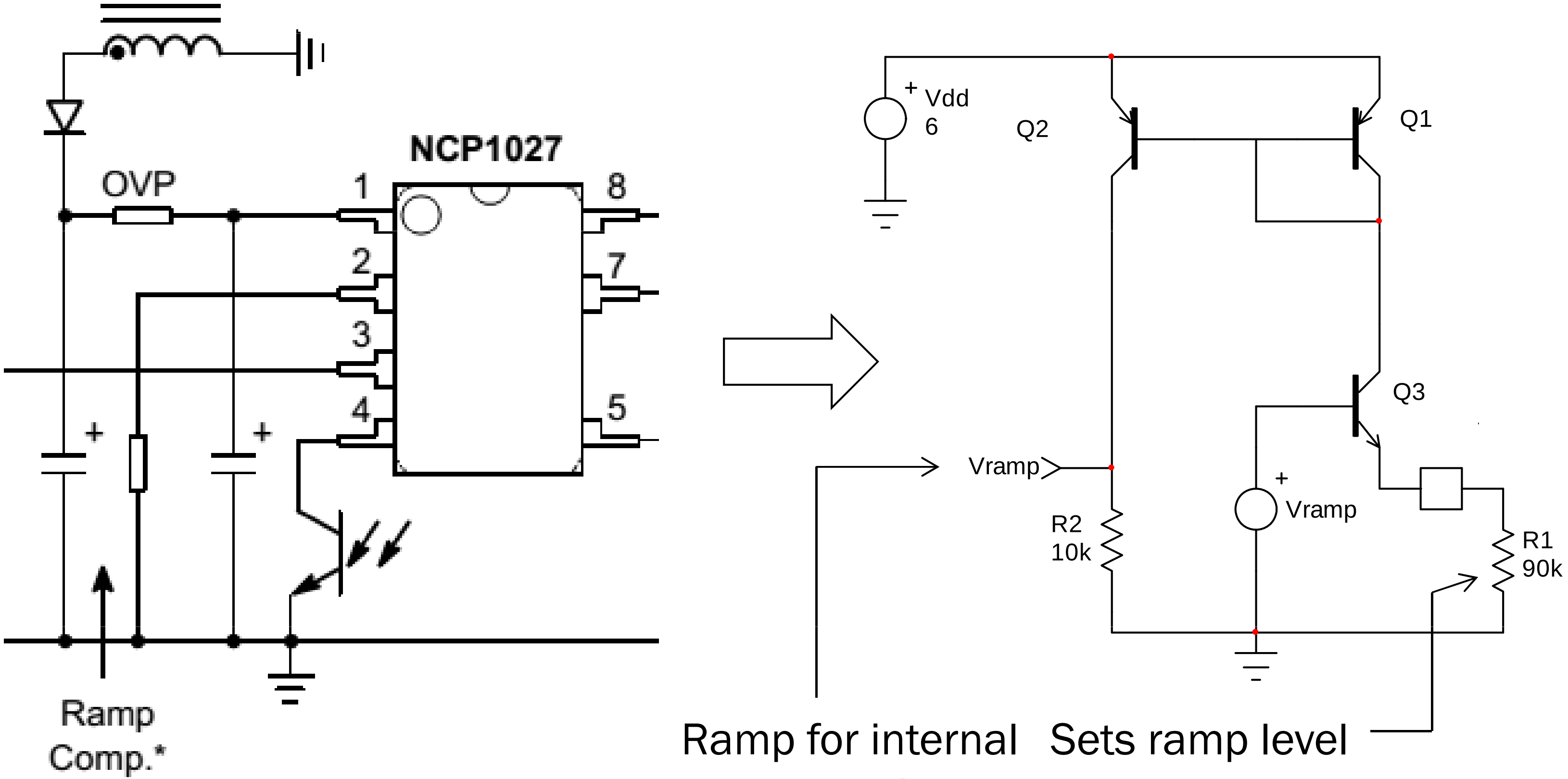


Adjust the resistor to set the ramp to any level

NCP1250

Slope Compensation in a Switcher

- ❑ In a switcher, a current mirror duplicates the external current



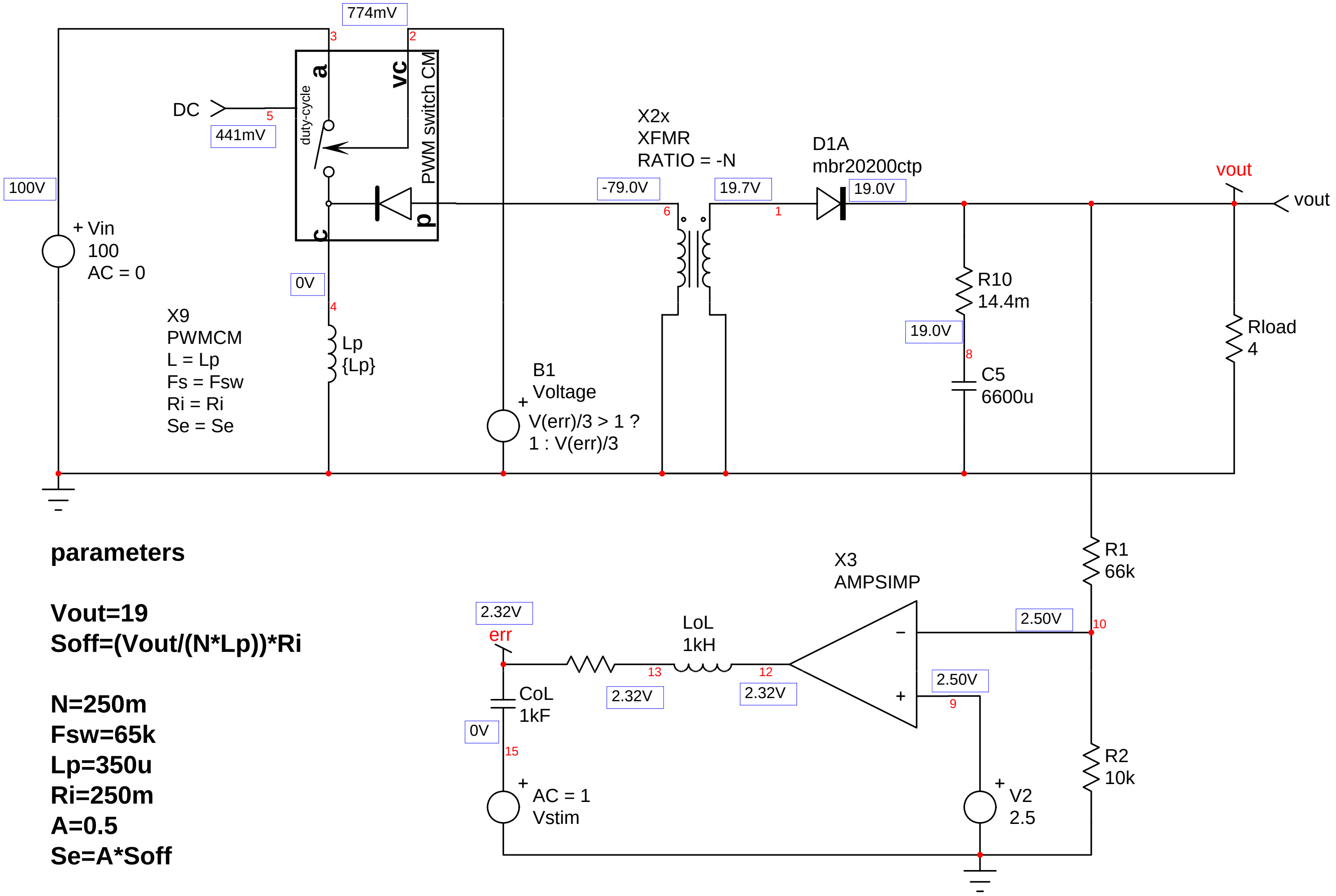
Ramp for internal compensation

Sets ramp level

NCP1027

Average Model Predicts Instabilities

- ☐ A SPICE model can show sub-harmonic instabilities



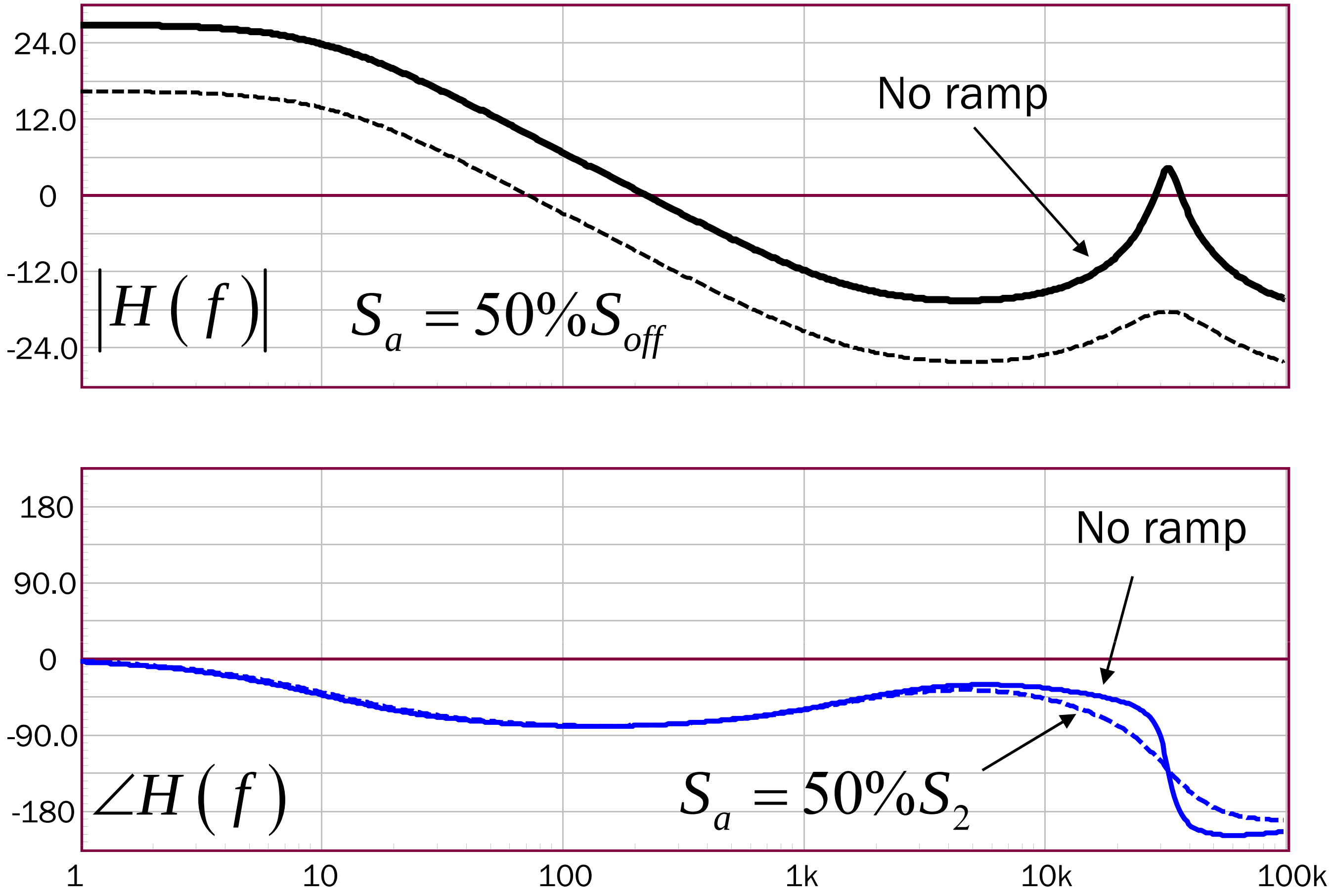
parameters

Vout=19
Soff=(Vout/(N*Lp))*Ri

N=250m
Fsw=65k
Lp=350u
Ri=250m
A=0.5
Se=A*Soff

Injecting Ramp to Damp the Poles

- ☐ As ramp is injected, the double-pole Q is damped
- ☐ Injecting more ramp turns the converter into voltage-mode



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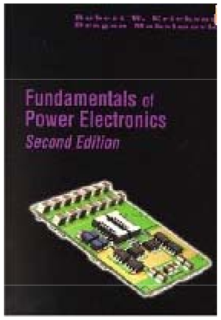
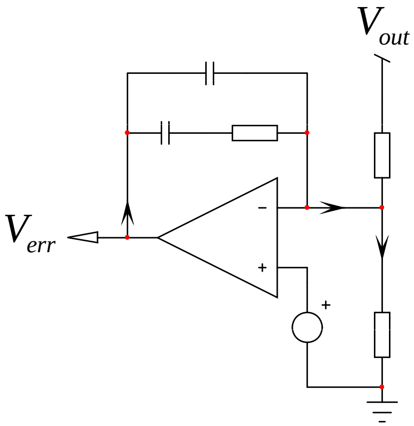
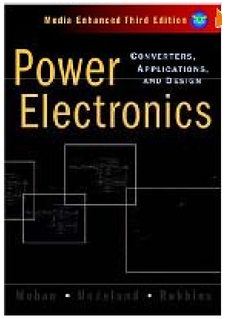
How do you Ensure Regulation?

- ❑ Text books only describe op amps in compensators…



Fundamentals of Power Electronics
Second Edition



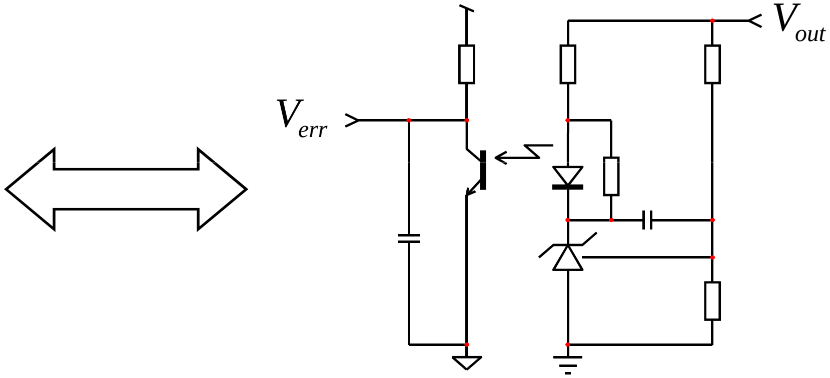


Media Enhanced Third Edition
Power Electronics
Converters, Applications, and Design
Mohan • Undeland • Robbins

- ❑ The market reality is different: the TL431 rules!

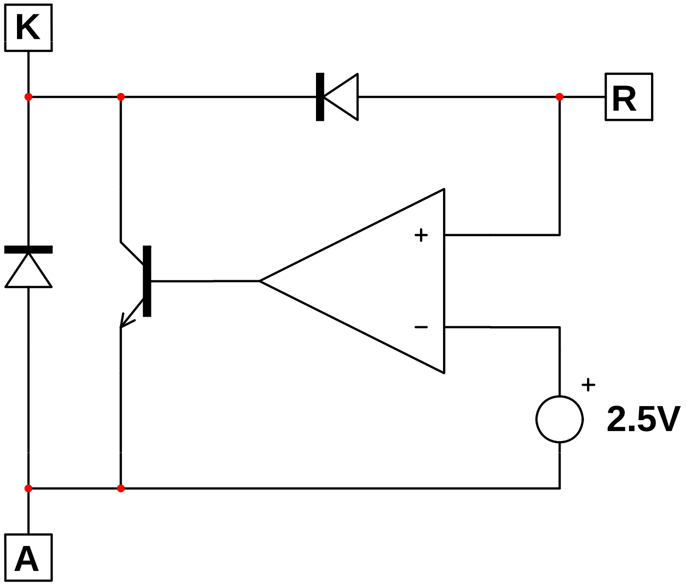
TL431

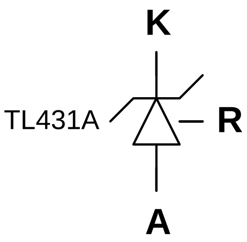
optocoupler

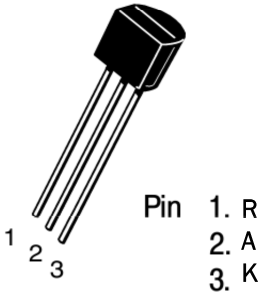


A Programmable Zener Diode

- 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



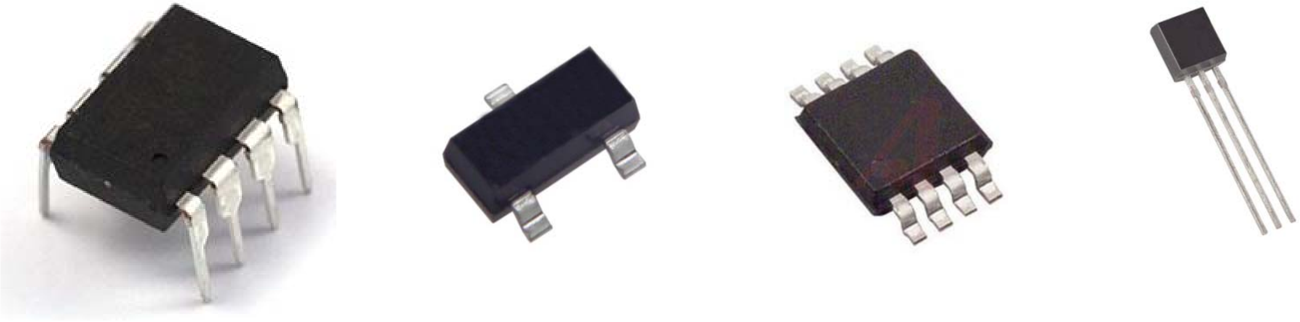




- The TL431 is a shunt regulator

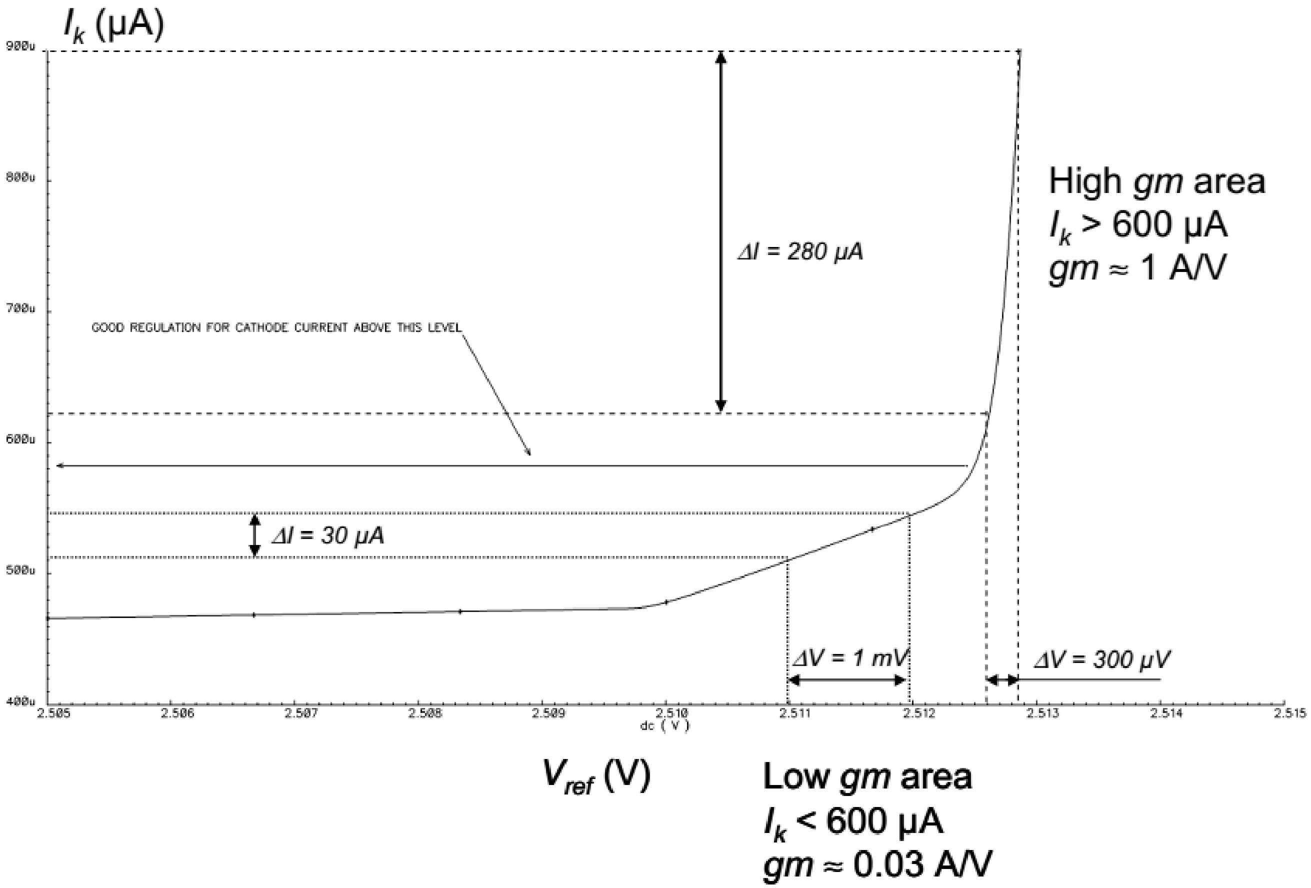
Different Types of TL431

Part number	Max voltage (V)	Min operating current (µA)	Reference voltage (V)	Packages
TL431	37	1000	2.5	TO92, SO8, µ8, DIP8
TLV431	18	100	1.24	TO92, TSOP5, SOT-23
NCP431	37	60	2.5	TO92, SO8, SOT-23
NCP100	7	100	0.9	TO92, TSOP5



Biasing the TL431

- ❑ The part needs a minimum bias current to operate properly



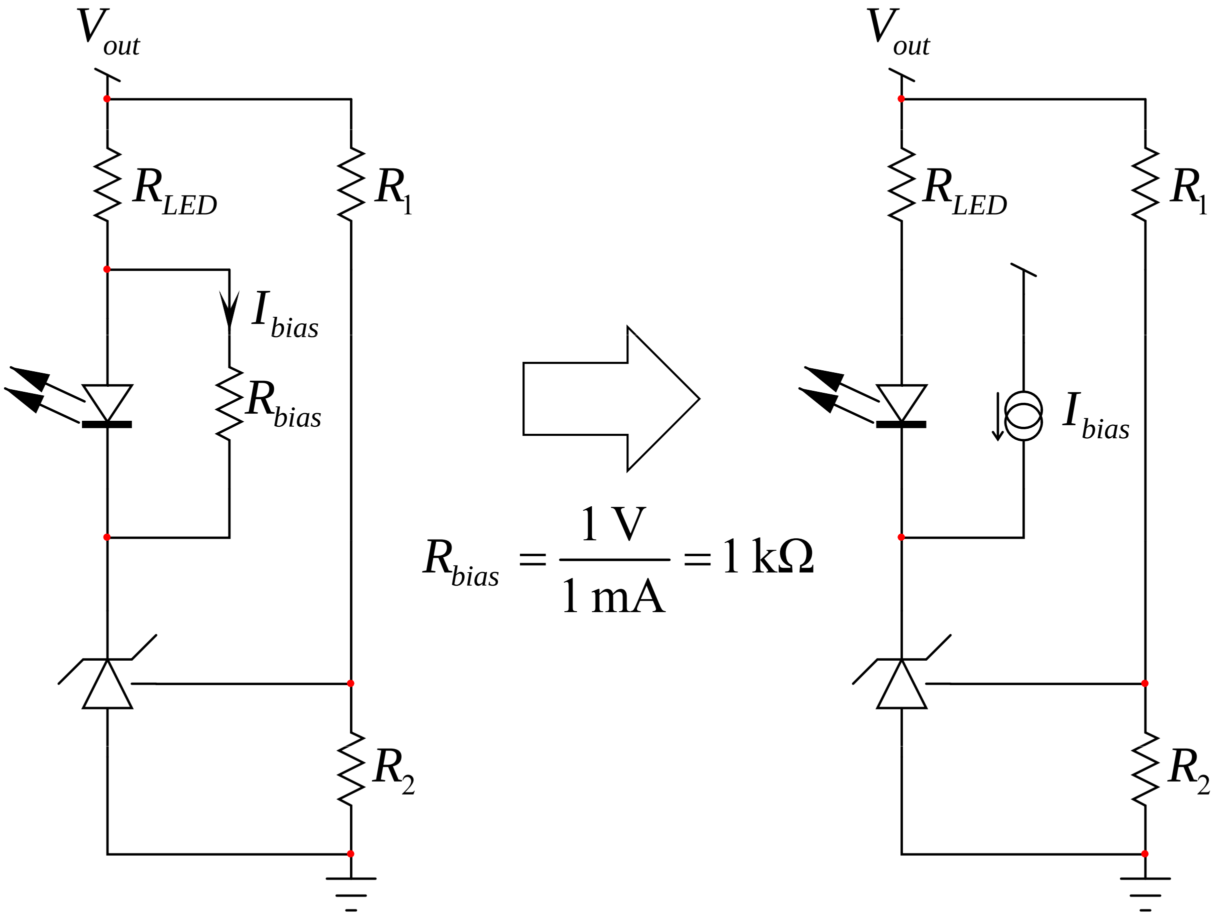
High *gm* area
$I_k > 600$ µA
$gm \approx 1$ A/V

Low *gm* area
$I_k < 600$ µA
$gm \approx 0.03$ A/V

- ❑ Too low a bias current degrades the open-loop gain

Simplest Biasing Technique

❑ The part needs a minimum bias current to deliver performance

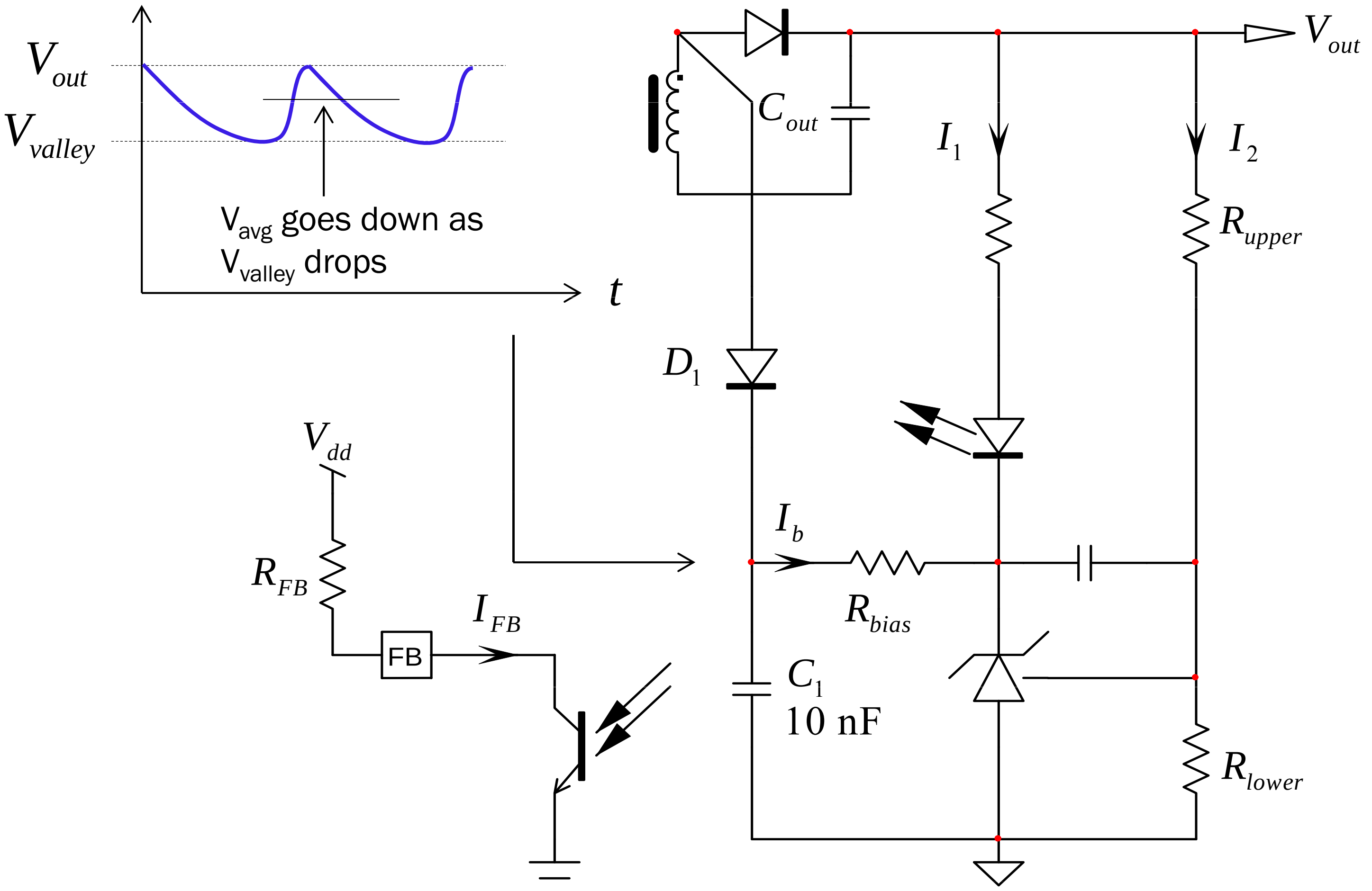


$$R_{bias} = \frac{1\ \text{V}}{1\ \text{mA}} = 1\ \text{k}\Omega$$

❑ The extra resistance provides the 1-mA bias in the easiest way

Suppressing the Bias Current in Standby

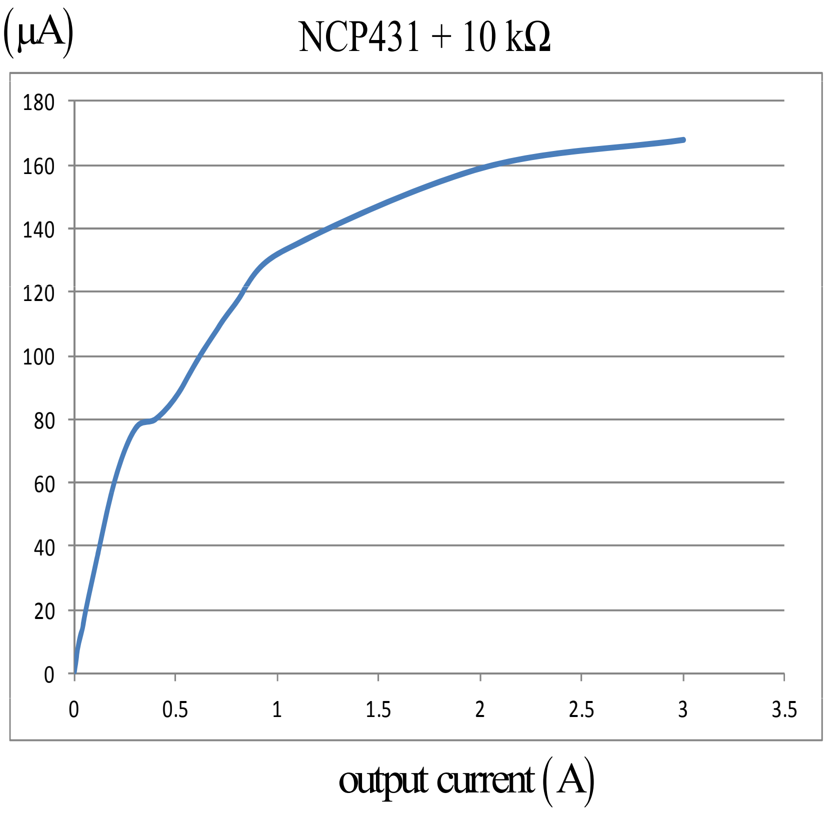
- ☐ When the converter enters skip cycle, the bias goes away

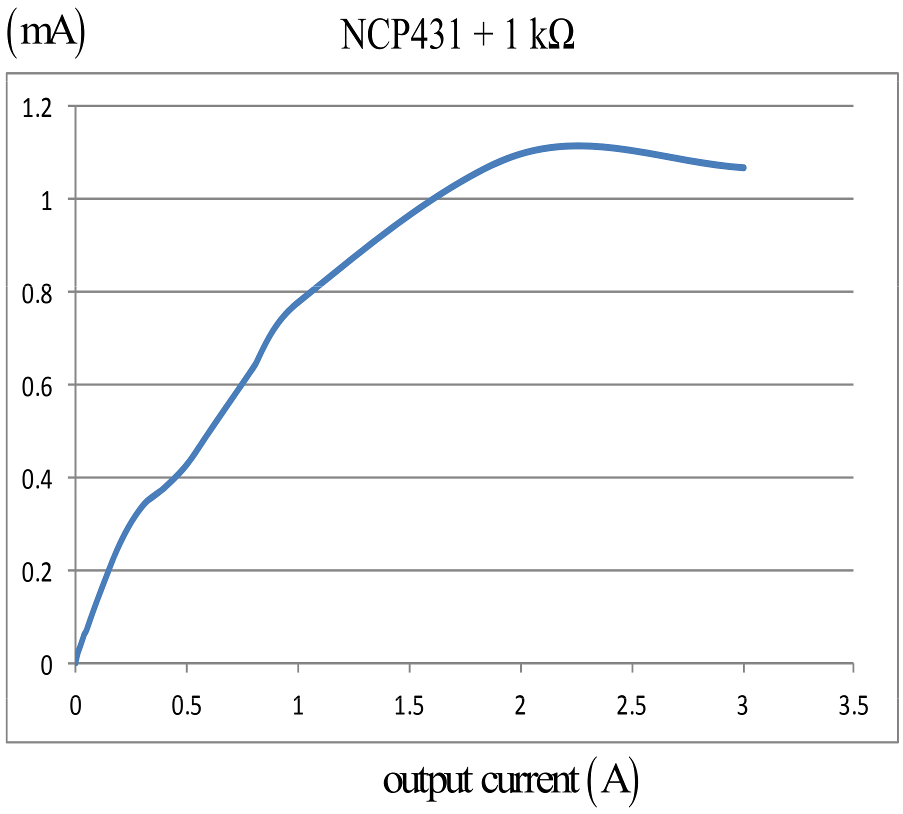


V_{avg} goes down as V_{valley} drops

The Bias Current Truly Reduces to 0 A

- In light-load conditions, the bias current reduces

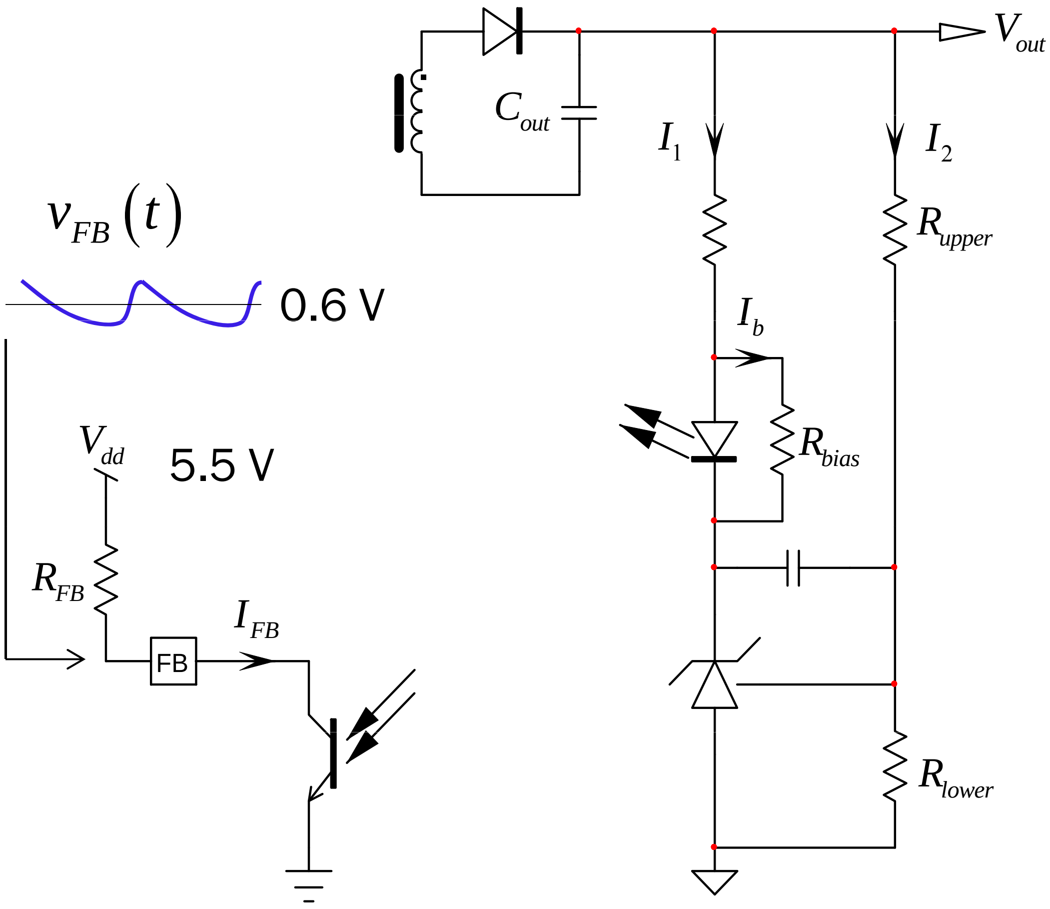

NCP431 + 10 kΩ


NCP431 + 1 kΩ

- In a no-load situation, it truly disappears and improves standby

How Can you Further Reduce Bias?

- ☐ The optocoupler CTR affects the LED current



$$I_{FB} = \frac{5.5-0.6}{30\text{k}} \approx 163\ \mu\text{A}$$

$$I_{LED} = \frac{I_{FB}}{\text{CTR}} = \frac{163u}{0.3} = \boxed{543\ \mu\text{A}}$$

-2 grade

Affects standby

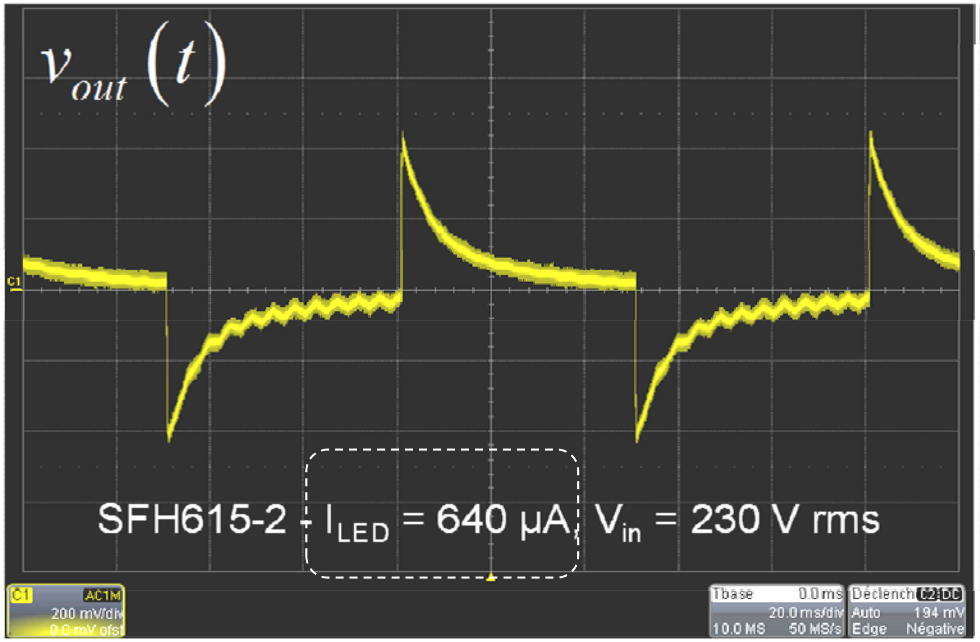
Select higher CTR grade optocouplers

$$I_{LED} = \frac{I_{FB}}{\text{CTR}} = \frac{163u}{0.75} = \boxed{217\ \mu\text{A}}$$

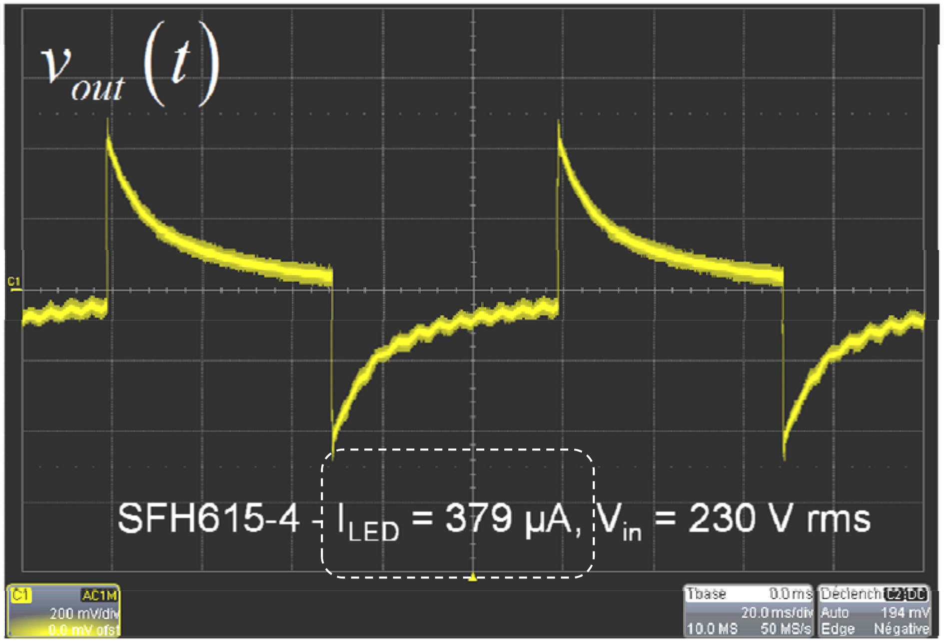
-4 grade

Watch Stability when Changing Opto

- High-CTR optocouplers have a lower low-frequency pole



12 mW for a 19-V output



7.2 mW for a 19-V output

- Check if transient response is not affected when upgrading

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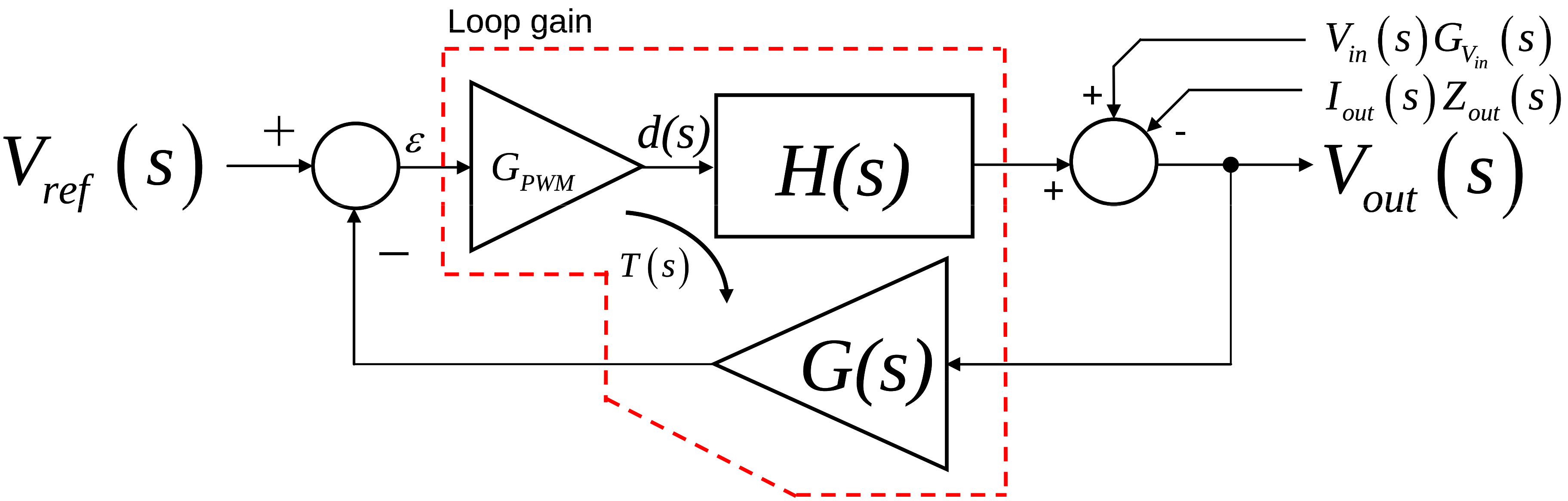
☐ **Building a Type 2 Compensator**

☐ A Design Example

What is a Type 2 Compensator?

- ☐ A current-mode converter exhibits a 1-st order response

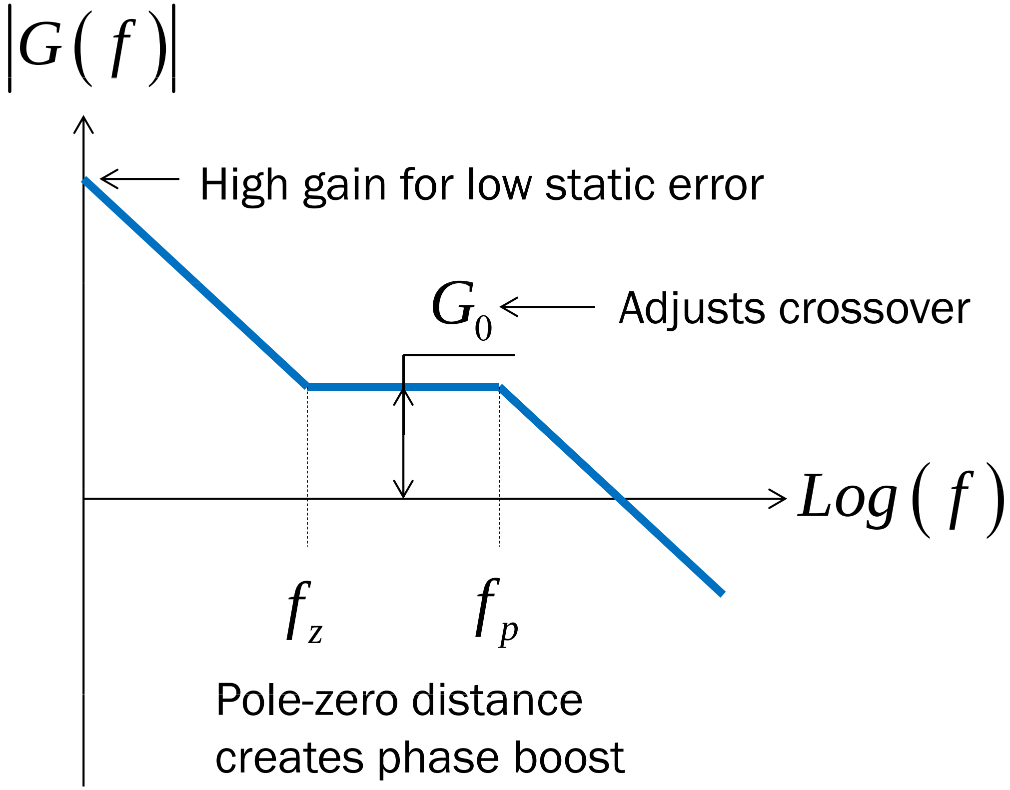


- ☐ One origin pole, one pole and one zero can compensate

⇨ Type 2 compensator

What is the Ac Response of a Type 2?

- Type 2 includes: origin pole, 1 pole and 1 zero



High gain for low static error

Adjusts crossover

Pole-zero distance creates phase boost

$$G_0 = \mathrm{CTR}\frac{R_{pullup}}{R_{LED}}$$

$$\omega_{z_1} = \frac{1}{R_1C_1}$$

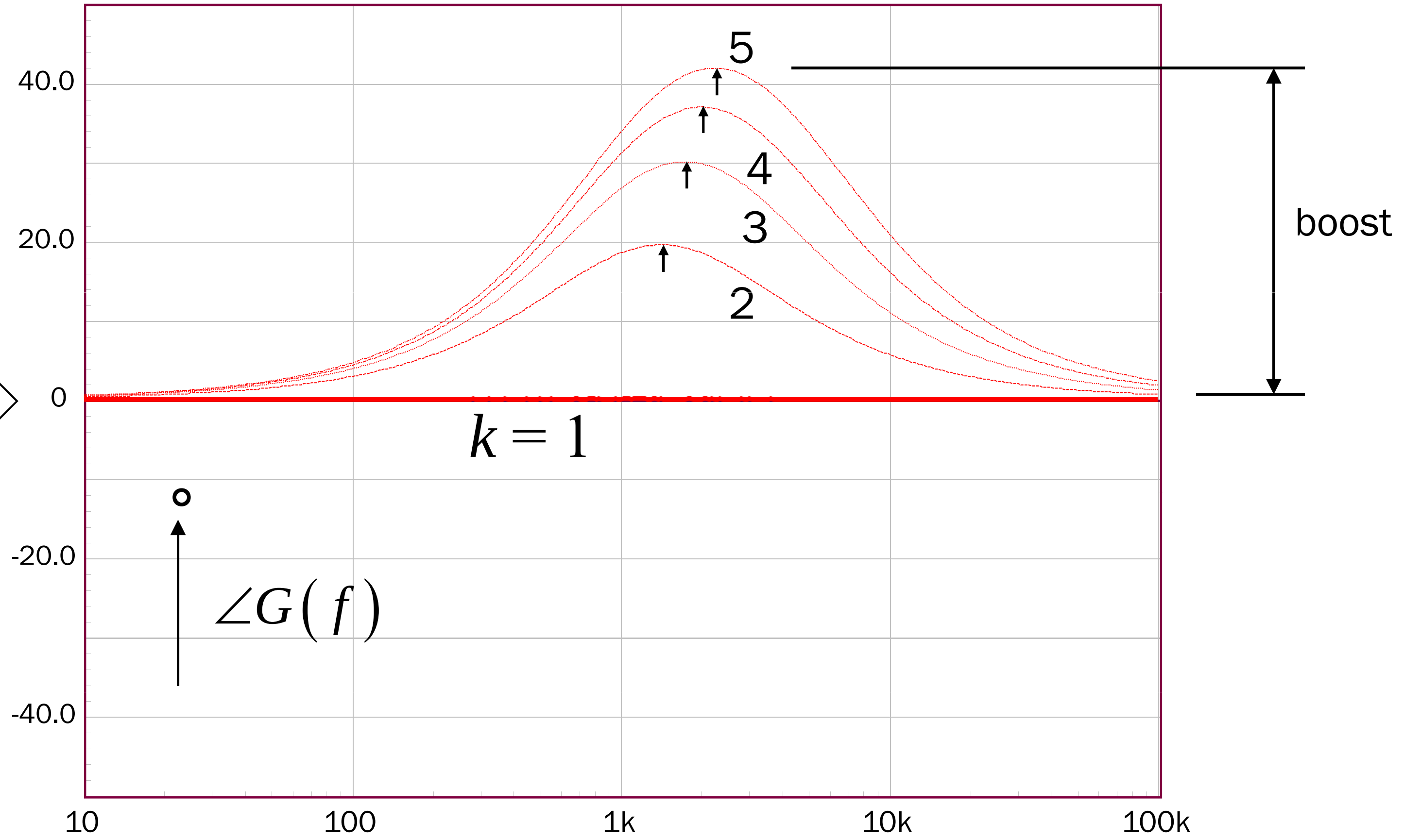
$$\omega_{p_1} = \frac{1}{R_{pullup}C_2}$$

- C_2 is an extra capacitor paralleled with the opto parasitics

Phase Boost Peaks between Pole and Zero

- The phase response peaks between the zero and the pole

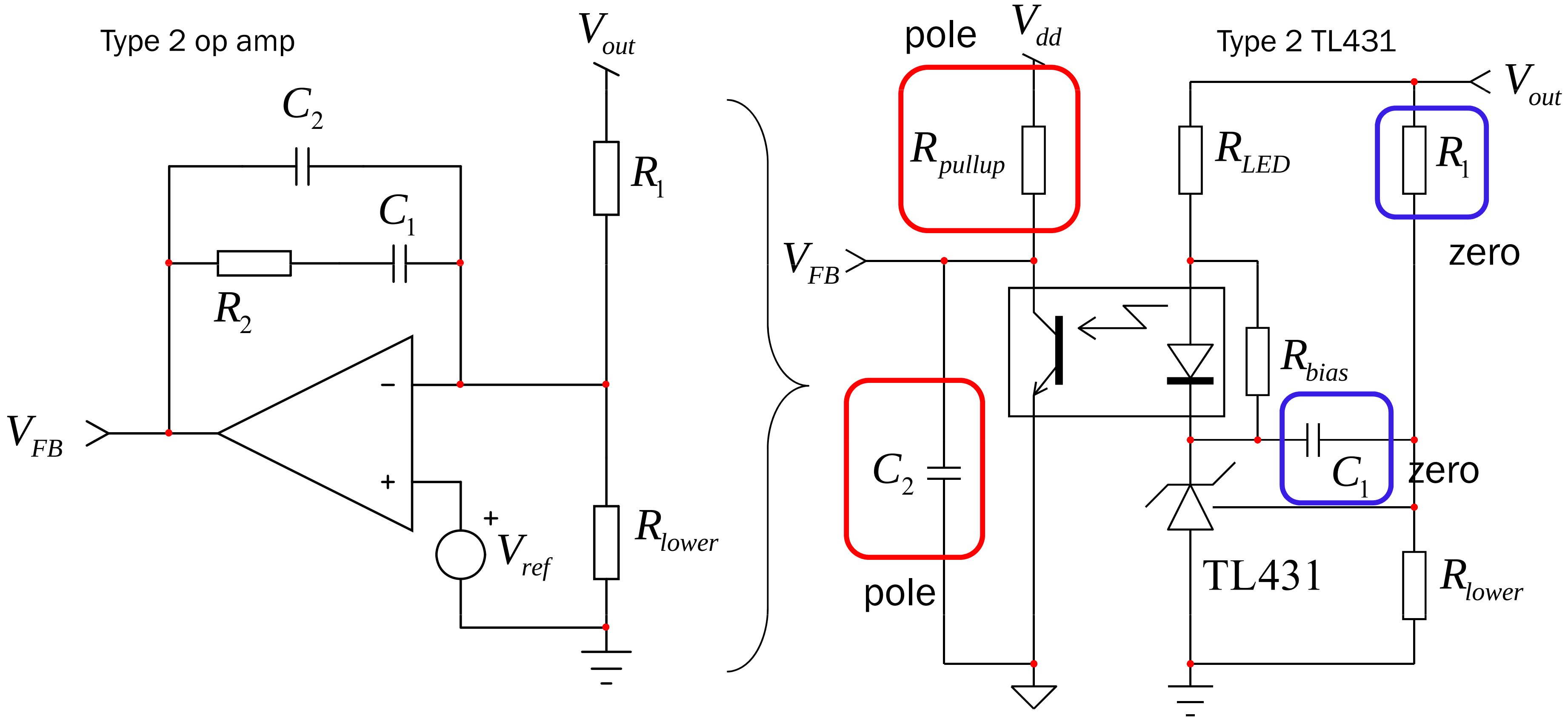
$$f_z = \frac{f_p}{k}$$



- This so-called phase boost helps build phase margin at f_c

From Op Amp to a TL431

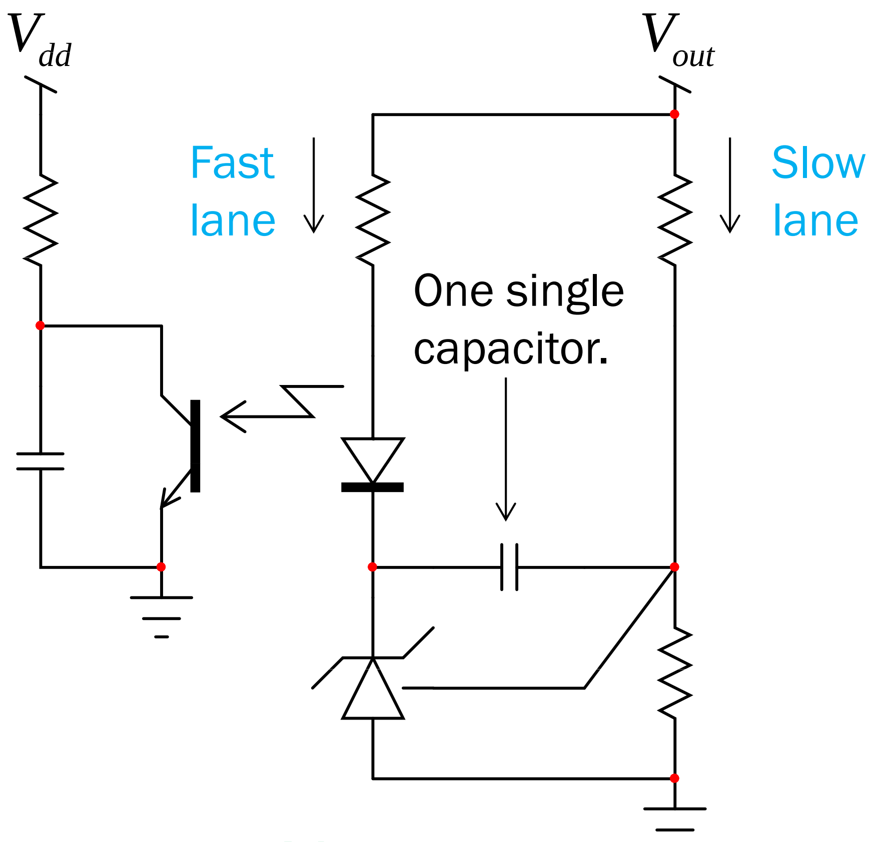
- ☐ A type 2 op amp-based requires a few passive components



- ☐ A single capacitor across the TL431 is enough to form a type 2

A Type 2 Requires One Capacitor!

☐ A genuine type 2 compensator requires a single capacitor

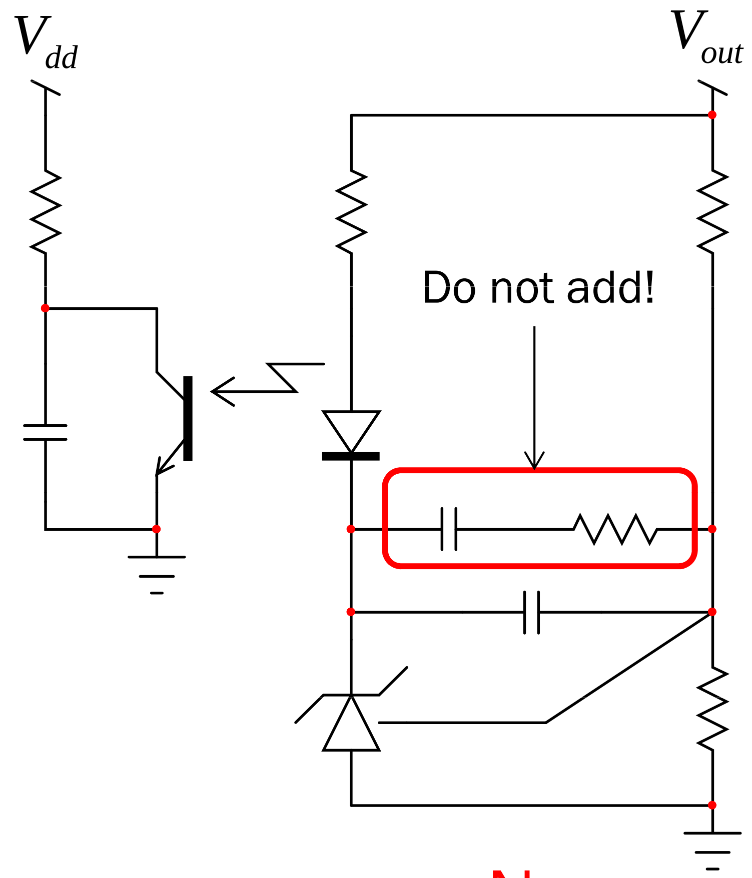


Fast lane

Slow lane

One single capacitor.

Yes



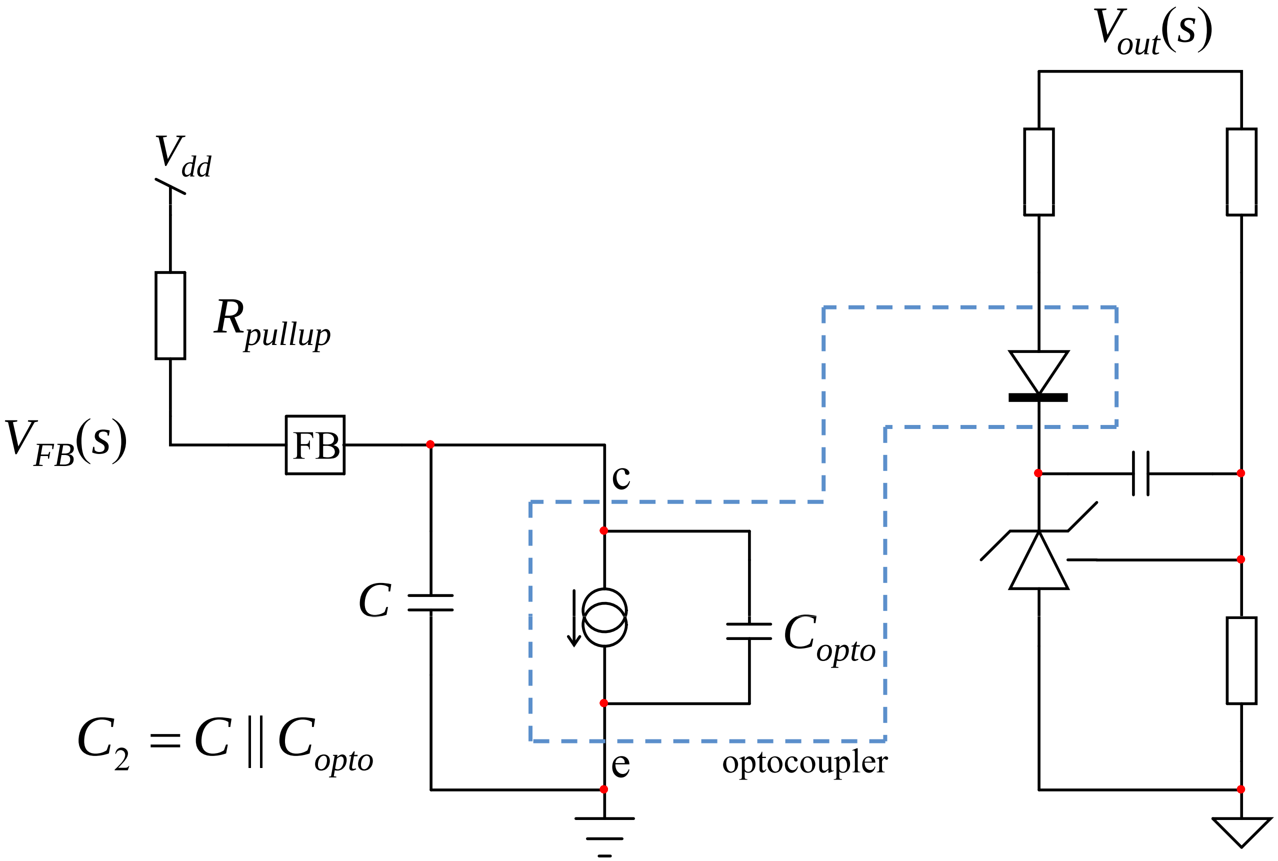
Do not add!

No

Optocoupler Pole Contribution

❑ The optocoupler features a parasitic capacitor

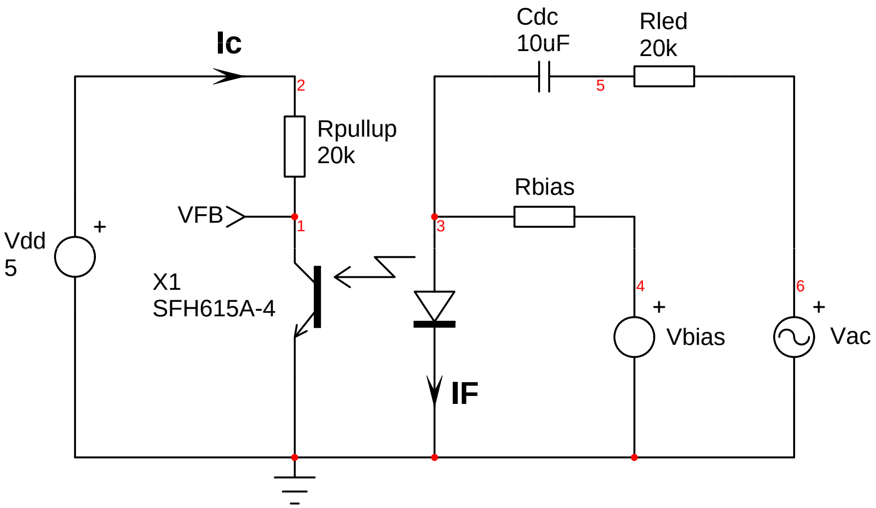
➢ It comes in parallel with C_2 and must be accounted for

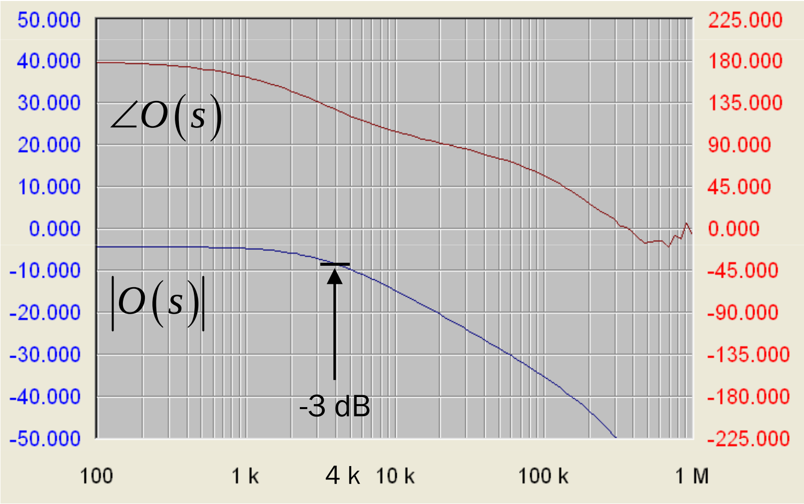


$$C_2 = C \parallel C_{opto}$$

Always Check the Pole Location

- ☐ The optocoupler must be characterized to know where its pole is





- ☐ Adjust V_{bias} to have V_{FB} at 2-3 V to be in linear region, then ac sweep
- ☐ The pole in this example is found at 4 kHz

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

⇨ Another design constraint!

TL431 Type 2 Design Example (I)

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

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

$$f_z = f_c^{\,2} / f_p = 25k/13.7k \approx 1.8\ \text{kHz} \qquad G_0 = \text{CTR}\frac{R_{pullup}}{R_{LED}} = 10^{15/20} = 5.62$$

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

$$R_{lower} = 2.5/250u = 10\ \text{k}\Omega \qquad R_1 = (12-2.5)/250u = 38\ \text{k}\Omega$$

- ☐ The pole and zero respectively depend on R_{pullup} and R_1:

$$C_2 = 1/2\pi f_p R_{pullup} = 581\ \text{pF} \qquad C_1 = 1/2\pi f_z R_1 = 2.3\ \text{nF}$$

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

$$R_{LED} = \frac{R_{pullup}\text{CTR}}{G_0} = 1.06\ \text{k}\Omega \xrightarrow{\text{ok}} R_{LED,\max} \le 4.85\ \text{k}\Omega$$

TL431 Type 2 Design Example (II)

- The optocoupler has a pole at 4 kHz:

$$C_{pole} \approx \boxed{2\text{ nF}}$$

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:

$$f_{pole} = \frac{1}{2\pi R_{pullup} C} = \frac{1}{6.28 \times 20k \times 2.1n} = 3.8\text{ kHz}$$

- For a 50° phase boost and a 3.8-kHz pole, the crossover must be:

$$f_c = \frac{f_p}{\tan\left(boost\right) + \sqrt{\tan^2\left(boost\right) + 1}} \approx 1.4\text{ kHz}$$

TL431 Type 2 Design Example (III)

- The zero is then simply obtained:

$$f_z = \frac{f_c^{\,2}}{f_p} = 516\ \mathrm{Hz}$$

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

$$C_2 = 1/2\pi f_p R_{pullup} = 2.1\ \mathrm{nF} \qquad C_1 = 1/2\pi f_z R_1 = 8.1\ \mathrm{nF}$$

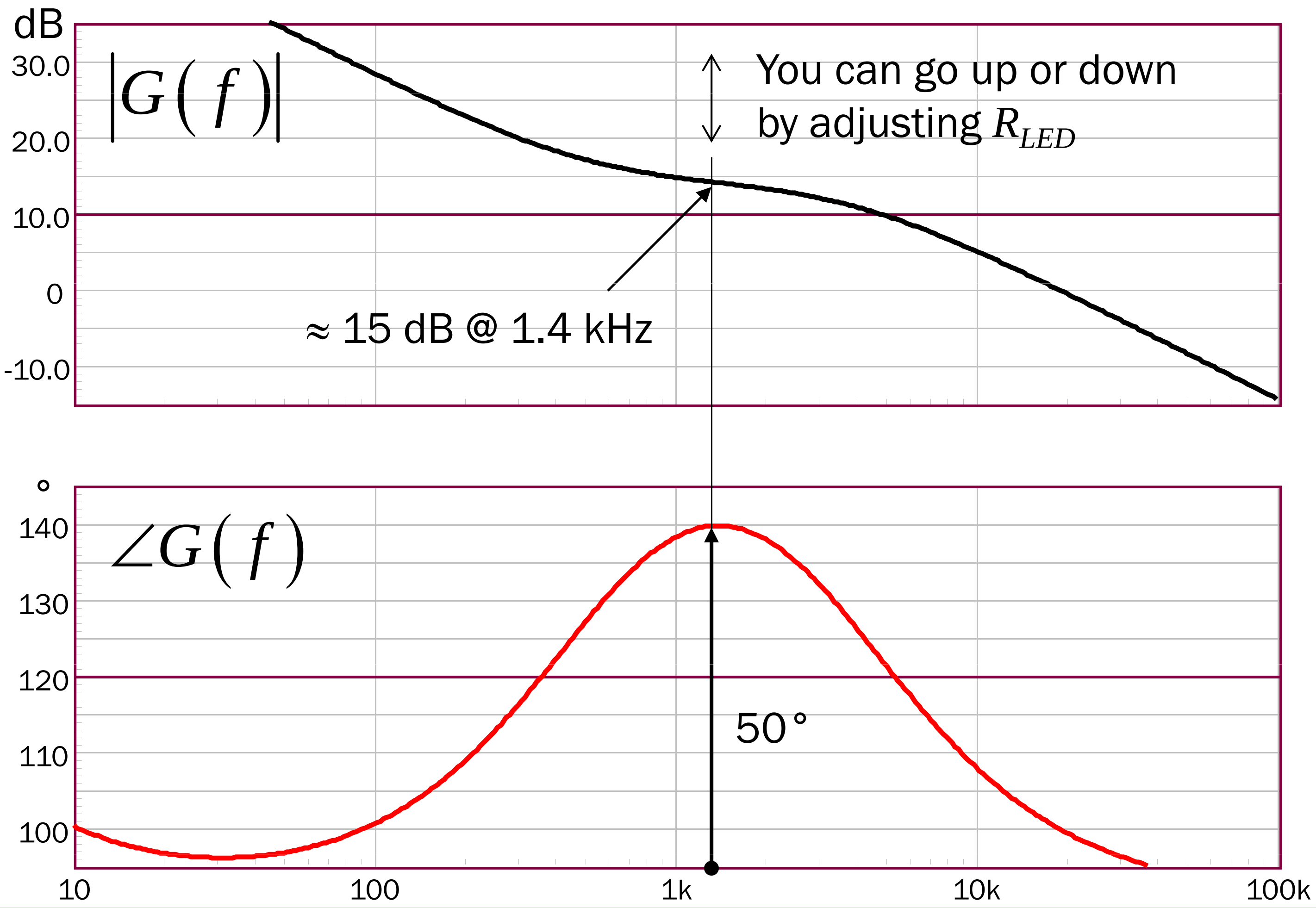
- Given the 2-nF optocoupler capacitor, we just add 100 pF
- To change the crossover, R_{LED} can be adjusted slightly

❖ However, if made too high, regulation can be lost

⇨ Always check bias conditions if you change R_{LED}

TL431 Type 2 Design Example (IV)

- ☐ A quick simulation shows phase/gain curves matching our calculations



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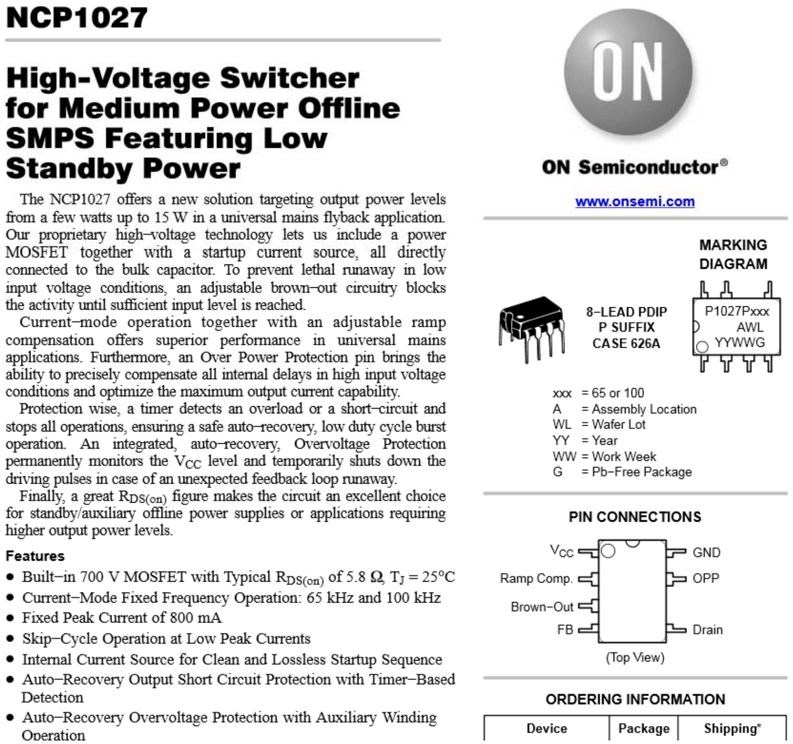
A CCM Converter with NCP1027

☐ Assume the following set of specifications:

$V_{in,min} = 120\ \text{V}$
$V_{out} = 12\ \text{V}$
$P_{out} = 10\ \text{W}$
$R_{load} = 14.4\ \Omega$
$F_{sw} = 65\ \text{kHz}$
$C_{out} = 3000\ \mu\text{F}$
$r_C = 100\ \text{m}\Omega$
$L_p = 3\ \text{mH}$
$N = 0.177$
$\text{CTR} = 30\%$
$R_{upper} = 38\ \text{k}\Omega$
$R_{pullup} = 10\ \text{k}\Omega$

NCP1027 is selected



NCP1027

High-Voltage Switcher for Medium Power Offline SMPS Featuring Low Standby Power

The NCP1027 offers a new solution targeting output power levels from a few watts up to 15 W in a universal mains flyback application. Our proprietary high−voltage technology lets us include a power MOSFET together with a startup current source, all directly connected to the bulk capacitor. To prevent lethal runaway in low input voltage conditions, an adjustable brown−out circuitry blocks the activity until sufficient input level is reached.

Current−mode operation together with an adjustable ramp compensation offers superior performance in universal mains applications. Furthermore, an Over Power Protection pin brings the ability to precisely compensate all internal delays in high input voltage conditions and optimize the maximum output current capability.

Protection wise, a timer detects an overload or a short−circuit and stops all operations, ensuring a safe auto−recovery, low duty cycle burst operation. An integrated, auto−recovery, Overvoltage Protection permanently monitors the V_{CC} level and temporarily shuts down the driving pulses in case of an unexpected feedback loop runaway.

Finally, a great $R_{DS(on)}$ figure makes the circuit an excellent choice for standby/auxiliary offline power supplies or applications requiring higher output power levels.

Features

- Built−in 700 V MOSFET with Typical $R_{DS(on)}$ of 5.8 Ω, $T_J = 25°C$
- Current−Mode Fixed Frequency Operation: 65 kHz and 100 kHz
- Fixed Peak Current of 800 mA
- Skip−Cycle Operation at Low Peak Currents
- Internal Current Source for Clean and Lossless Startup Sequence
- Auto−Recovery Output Short Circuit Protection with Timer−Based Detection
- Auto−Recovery Overvoltage Protection with Auxiliary Winding Operation

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MARKING DIAGRAM

8−LEAD PDIP
P SUFFIX
CASE 626A

xxx = 65 or 100
A = Assembly Location
WL = Wafer Lot
YY = Year
WW = Work Week
G = Pb−Free Package

PIN CONNECTIONS

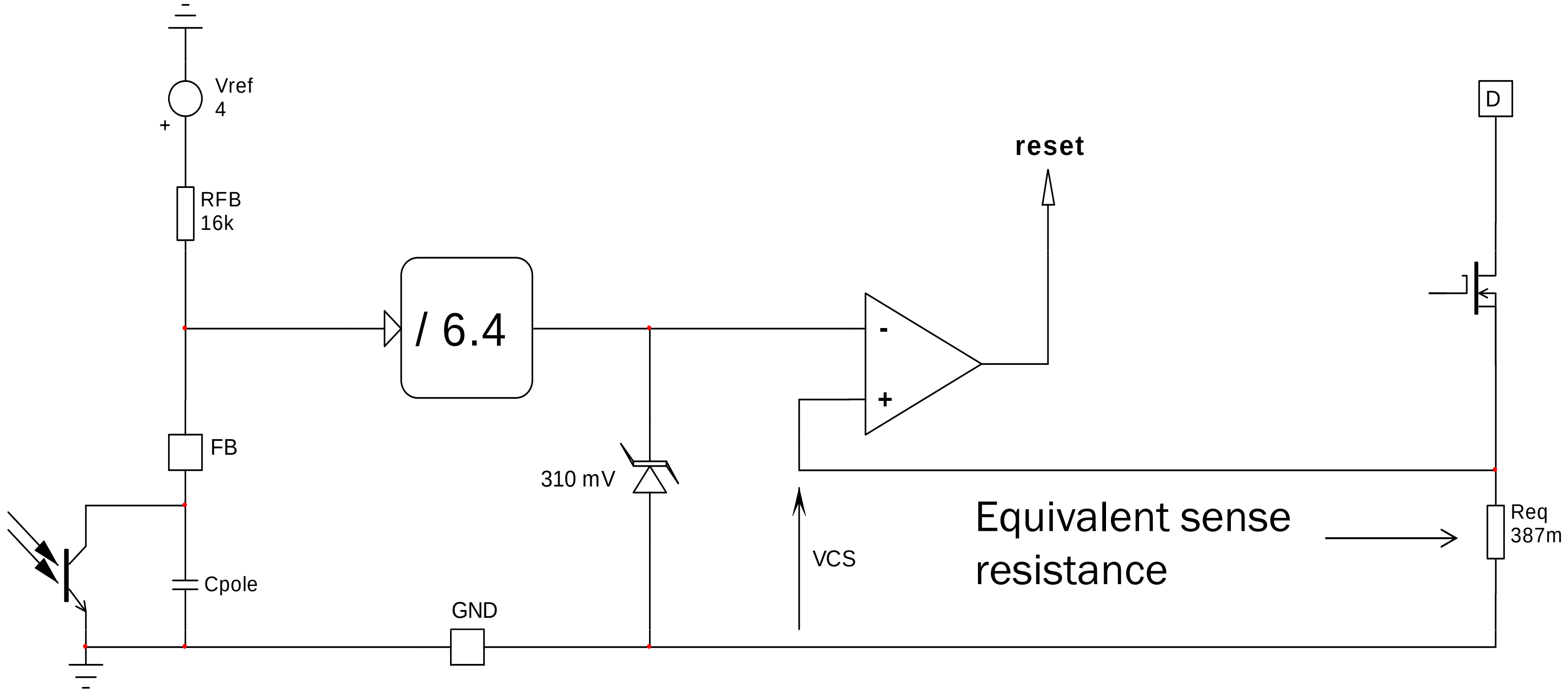
(Top View)

ORDERING INFORMATION

Device	Package	Shipping*

Internal Feedback Circuitry

- ☐ Internals reveal a voltage divider and an equivalent sense resistance



Equivalent sense resistance →

- ☐ These information are important to stabilize a converter using this part

Determining the Plant Response

- ☐ Before applying a compensation strategy, the plant response H is needed

Sub-harmonic poles

$$H(s) \approx H_0 \frac{\left(1+\frac{s}{\omega_{z_1}}\right)\left(1+\frac{s}{\omega_{z_2}}\right)}{1+\frac{s}{\omega_{p_1}}} \boxed{\frac{1}{1+\frac{s}{\omega_n Q_p}+\left(\frac{s}{\omega_n}\right)^2}}$$

$$H_0 = \frac{R_{load}}{R_{sense} G_{FB} N} \frac{1}{\frac{(1-D)^2}{\tau_L}+2M+1}$$

$$\tau_L = \frac{2L_p N^2}{R_{load} T_{sw}} \qquad f_{p1} = \frac{\frac{(1-D)^3}{\tau_L}+1+D}{2\pi R_{load} C_{out}} \qquad f_{z_1} = \frac{1}{2\pi \boxed{r_C} C_{out}} \qquad f_{z_2} = \frac{(1-D)^2 R_{load}}{2\pi D L_p N^2}$$

$$M = \frac{V_{out}}{N V_{in}} = \frac{12}{0.177 \times 120} = 0.564 \qquad D = \frac{V_{out}}{V_{out}+N V_{in}} = \frac{12}{12+0.177 \times 120} = 0.361$$

$$\tau_L = \frac{2L_p N^2}{R_{load} T_{sw}} = \frac{2 \times 3m \times 0.177^2}{14.4 \times 15.4u} = 0.848$$

Know the ESR

Get the Power Stage Ac Response

- ☐ Use a mathematical solver to obtain the power plant frequency response

Converter Parameters Fixed-Frequency Operation

$V_{in\_min} := 120V$ $V_{in\_max} := 370V$ $N_s := 17.7$ $R_{sense} := 0.25\Omega$ $C_{out} := 3000\mu F$

$V_{out} := 12V$ $L_p := 3000\mu H$ $N_p := 100$ $\eta := 85\%$ $R_{esr} := 0.1\Omega$

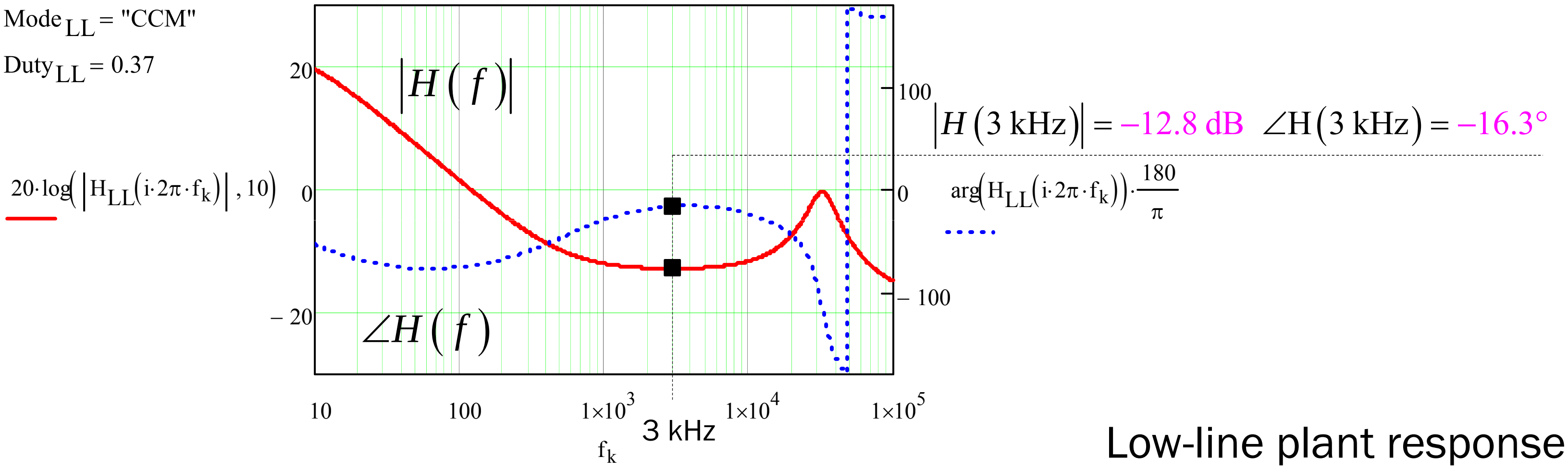
$P_{out} := 10W$ $V_f := 0.5V$ $N_1 := \frac{N_s}{N_p} = 0.177$ $R_{load} := \frac{V_{out}^2}{P_{out}} = 14.4\Omega$

Controller Parameters

$F_{sw} := 65kHz$ $S_e := 0\frac{kV}{s}$ $Div := 6.4$ $T_{sw} := \frac{1}{F_{sw}} = 15.385 \cdot \mu s$

$Mode_{LL} = "CCM"$

$Duty_{LL} = 0.37$



$|H(3\,kHz)| = -12.8\ dB$ $\angle H(3\,kHz) = -16.3°$

Low-line plant response

Select a Compensation Strategy

- Shift the gain by 13 dB (H_c) and boost the phase by

$$\text{Boost} = \text{PM} - \text{PS} - 90 = 70 + 16.3 - 90 \approx -3.7°$$

⇨ A negative phase boost indicates that no boost is necessary

- Place coincident pole and zero at f_c in this case:

$f_p = f_z = 3\ \text{kHz}$ ⇨ Build a type 1 compensator

- Calculate component values

$$R_{LED} = \text{CTR}\frac{R_{pullup}}{H_c} = 0.3 \times \frac{20k}{10^{\frac{13}{20}}} \approx 1.4\ \text{k}\Omega$$

$$C_2 = \frac{1}{2\pi f_p R_{pullup}} = \frac{1}{6.28 \times 3k \times 20k} \approx 2.6\ \text{nF}$$

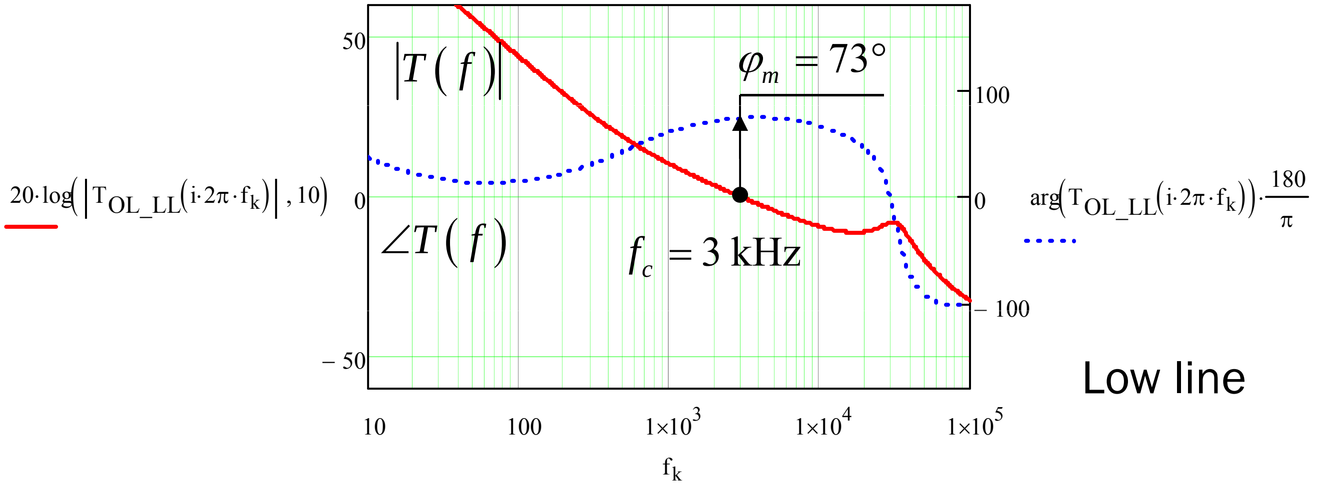
$$\Big\downarrow\ C_{opto} = 2\ \text{nF}$$

$$C = 680\ \text{pF}$$

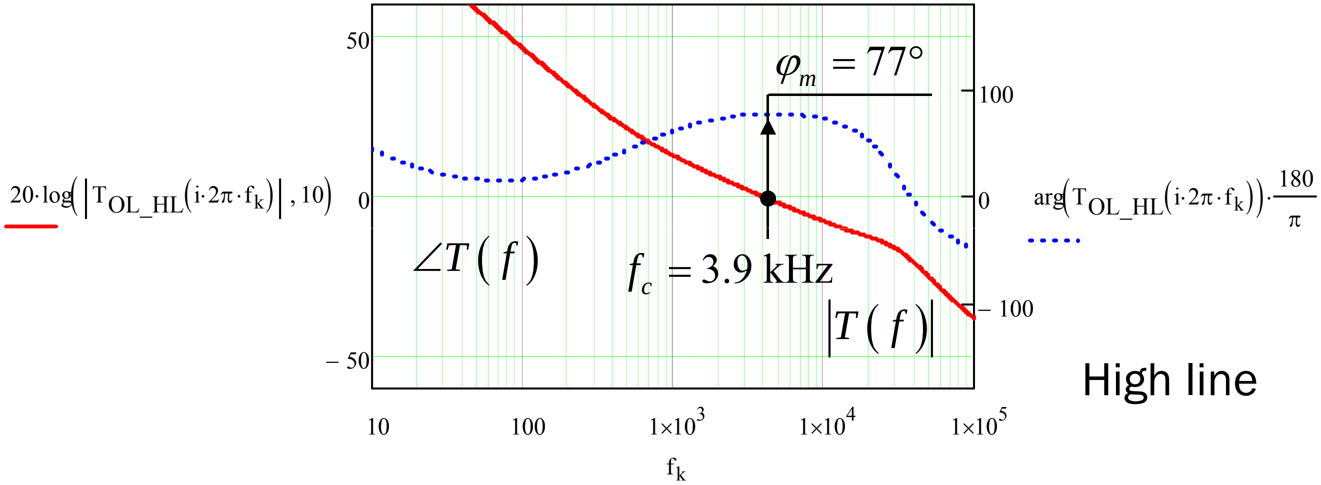
$$C_1 = \frac{1}{2\pi f_p R_{upper}} = \frac{1}{6.28 \times 3k \times 38k} \approx 1.4\ \text{nF}$$

Check Loop Gain at Different Voltages

☐ Verify phase margin in high and low line conditions



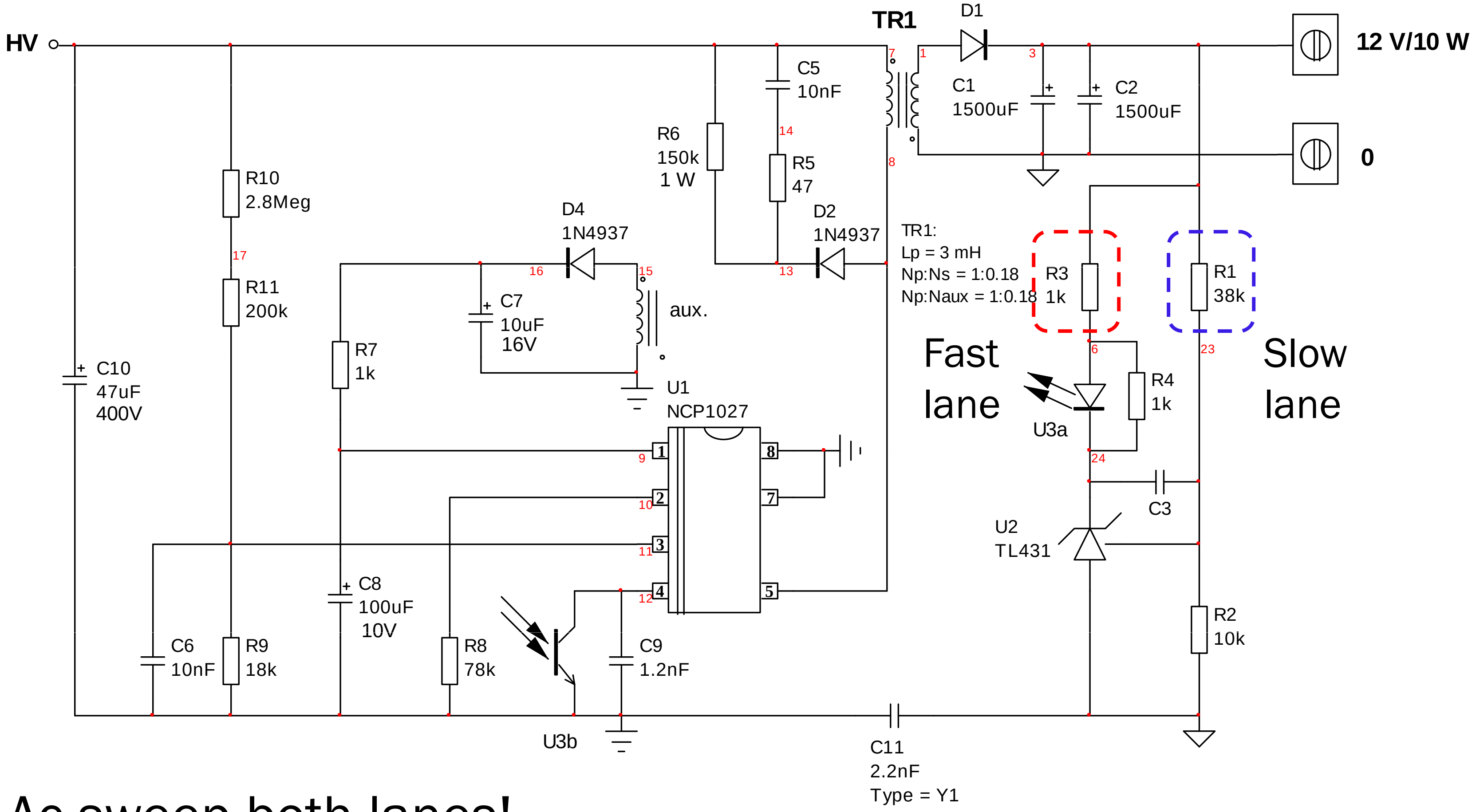
Low line



High line

Build a Prototype to Verify Assumptions

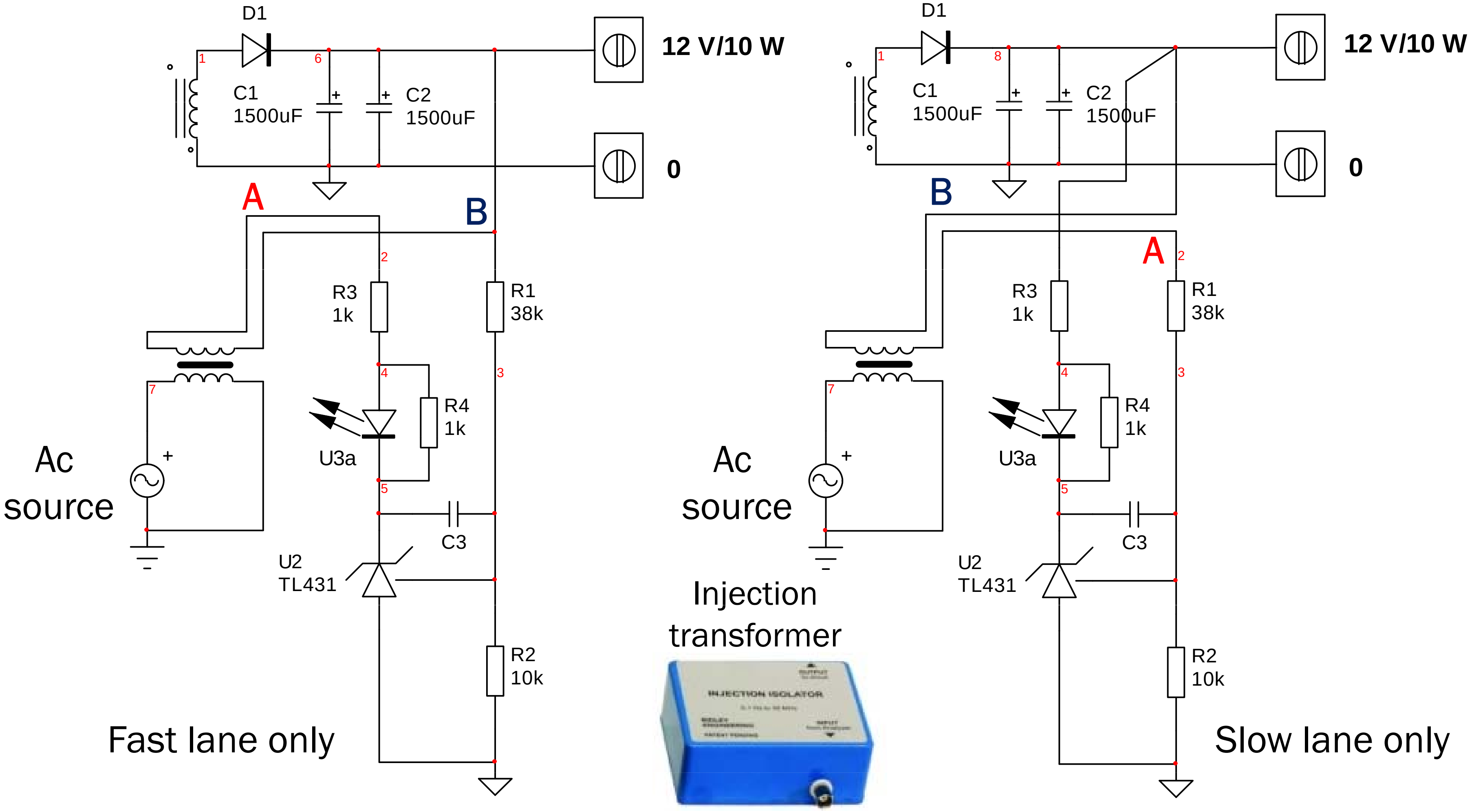
- ☐ Assemble a prototype and check stability



- ☐ Ac-sweep both lanes!

Do not Sweep one Single Lane

- ❑ A common mistake is to sweep one lane at a time



Ac source

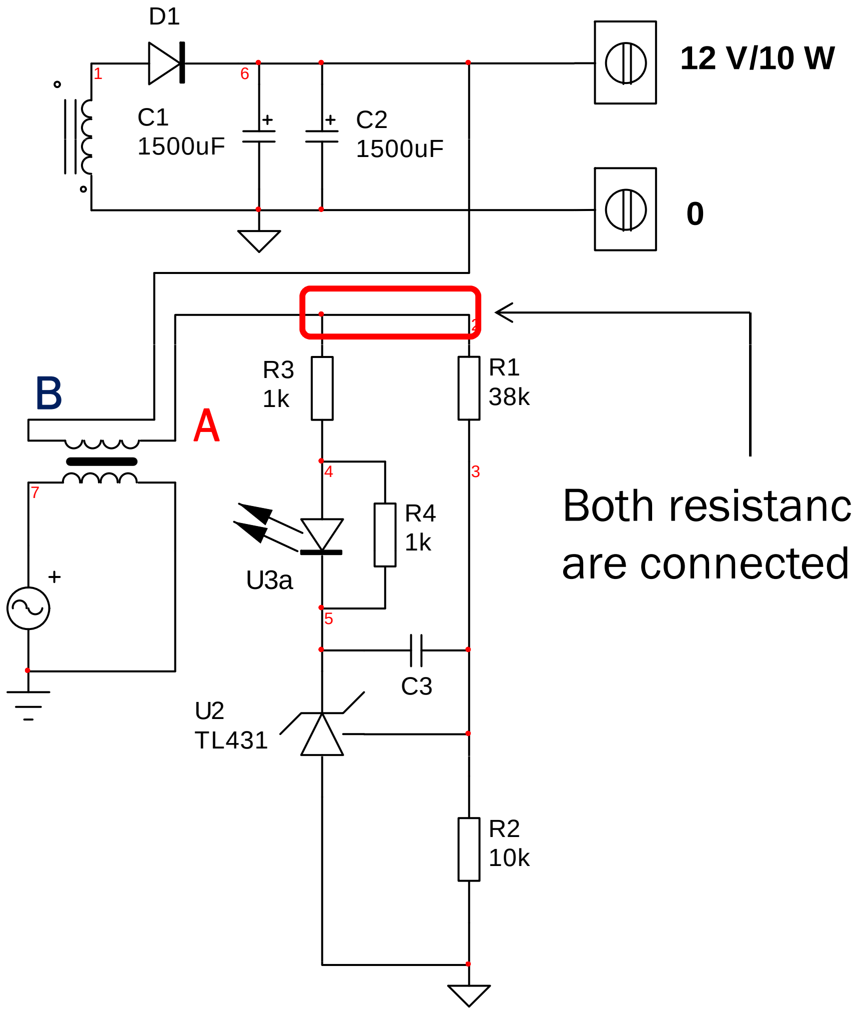
Injection transformer

Fast lane only

Slow lane only

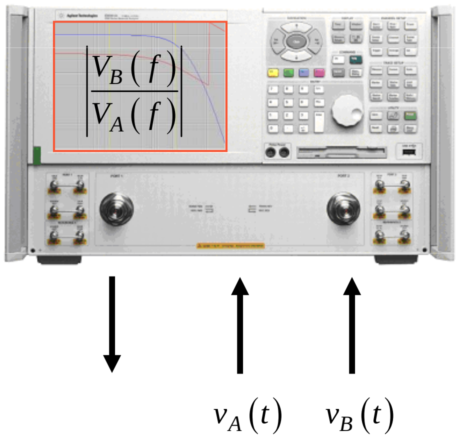
Make Sure Both Lanes are Swept

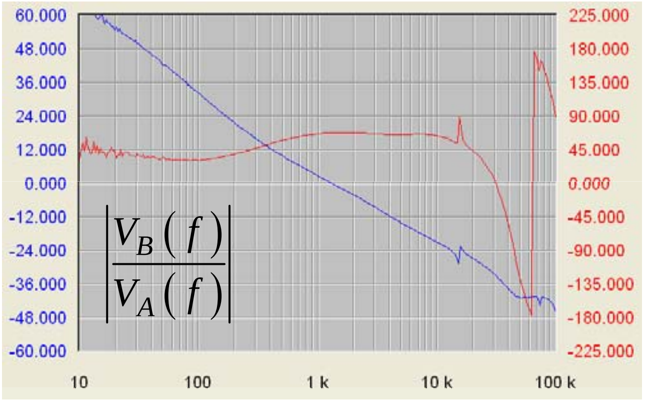
- ☐ Connect both resistances and inject in series



Both resistances
are connected together.

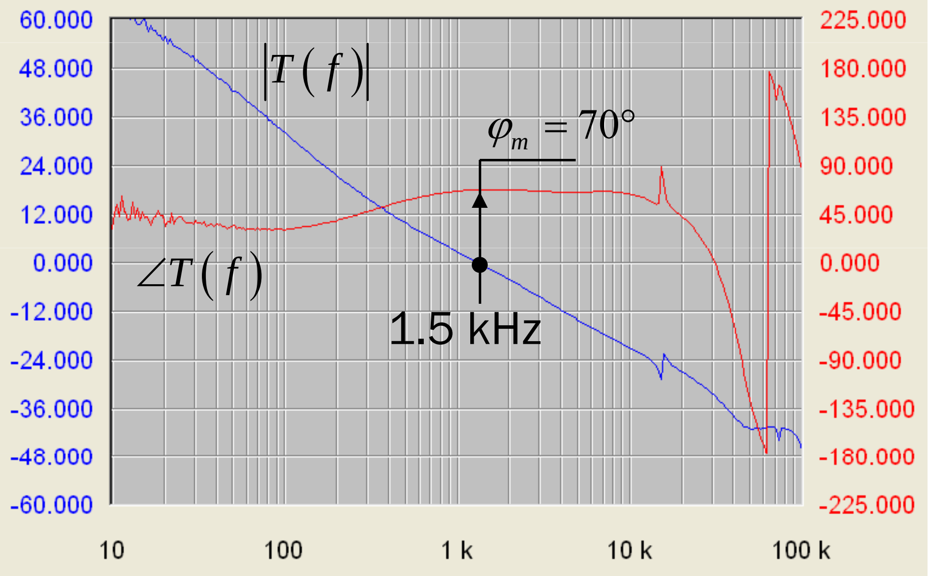
Network analyzer



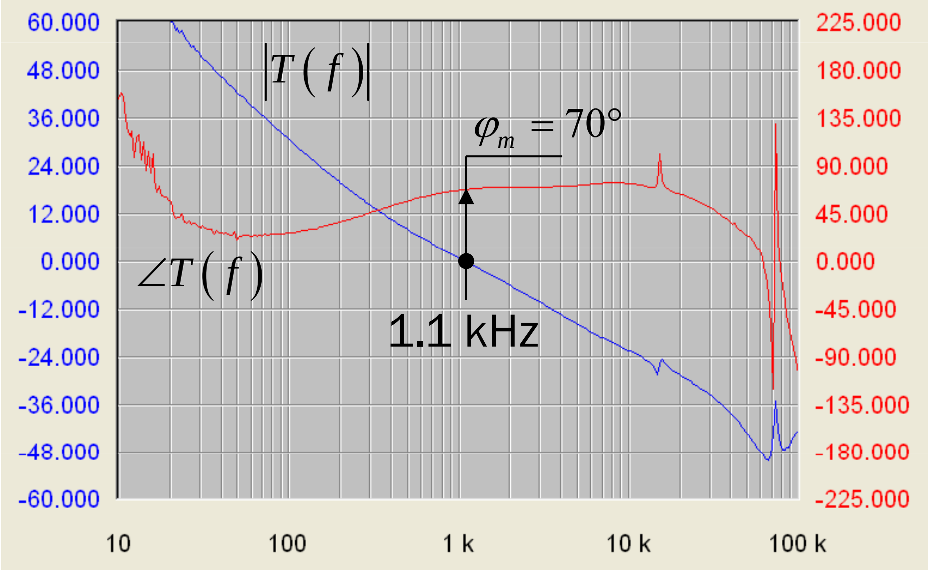


Explore both Operating Modes

❑ It is important to verify operations at low and high line



Low line - CCM



High line - DCM

❑ Dispersion in crossover can be linked to CTR spread

Conclusion

- ☐ Loop control strategy participates in converter's reliability
- ☐ It is important to understand all mechanisms
- ☐ Compensation requires analytical insights
- ❖ Trial and error is not acceptable!
- ☐ Analytical or SPICE models offer adequate tools
- ☐ Always measure loop gain on a prototype