Analog control of switched mode converters

Topic 5.

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Agenda

- Introduction
- Buck – Forward converter
  - Switching waveforms
  - Voltage mode control
  - Current mode control
  - Control-to-output function Gvc: using ic = iL approximation
  - Control-to-output function GvFB (including transformer and shunt resistor)
  - Controller function: Type II
- Implementation
- Controller design with Operational Amplifier
- Controller design with TL431 Shunt regulator
- Exercise

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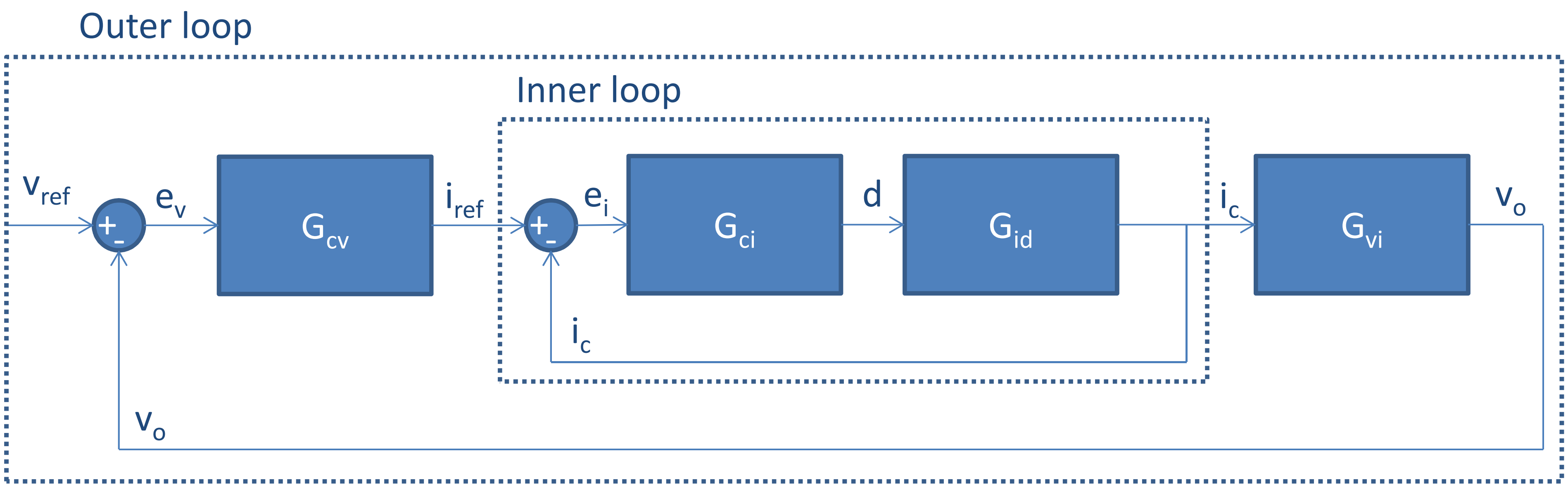
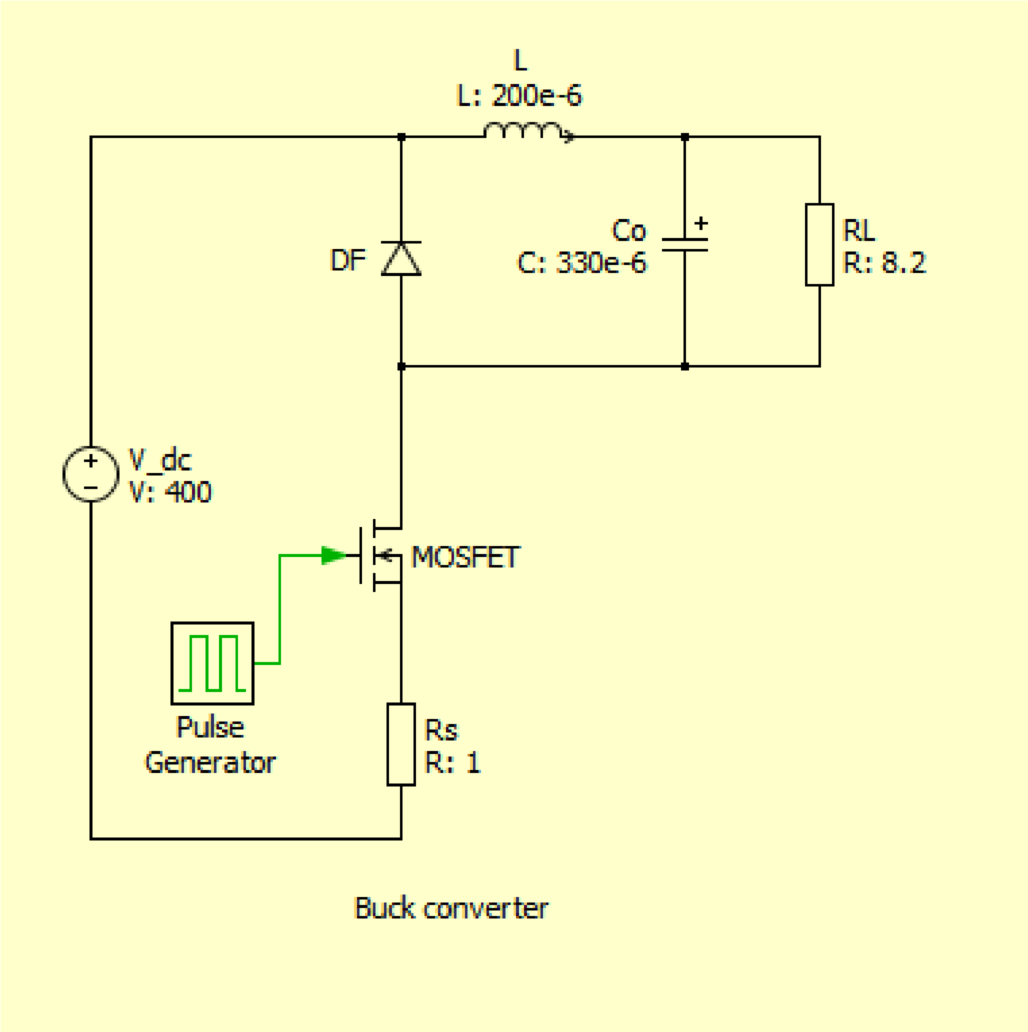
Introduction



Control structure for a switched mode power converter

Buck converter



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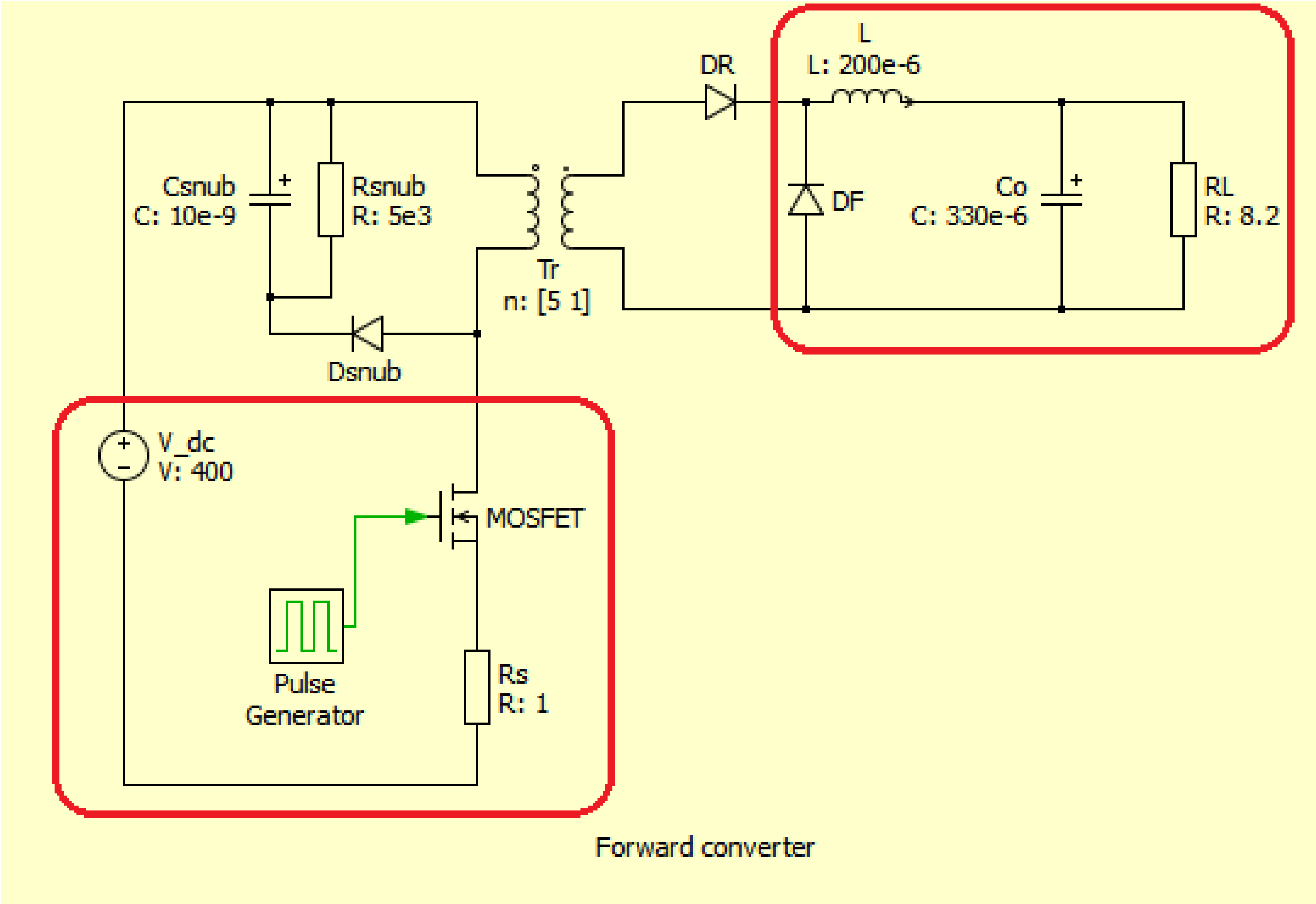
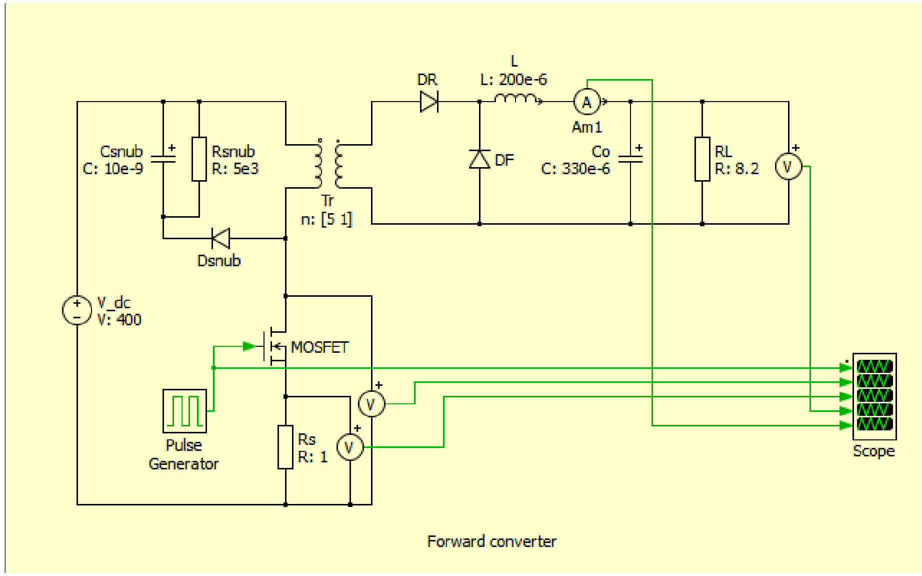
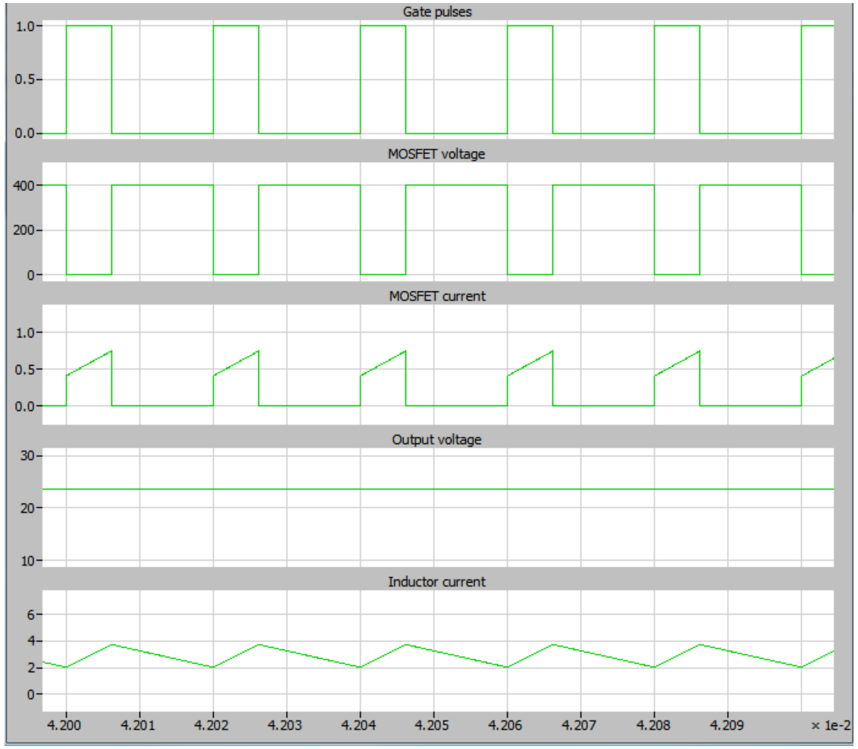
Forward converter

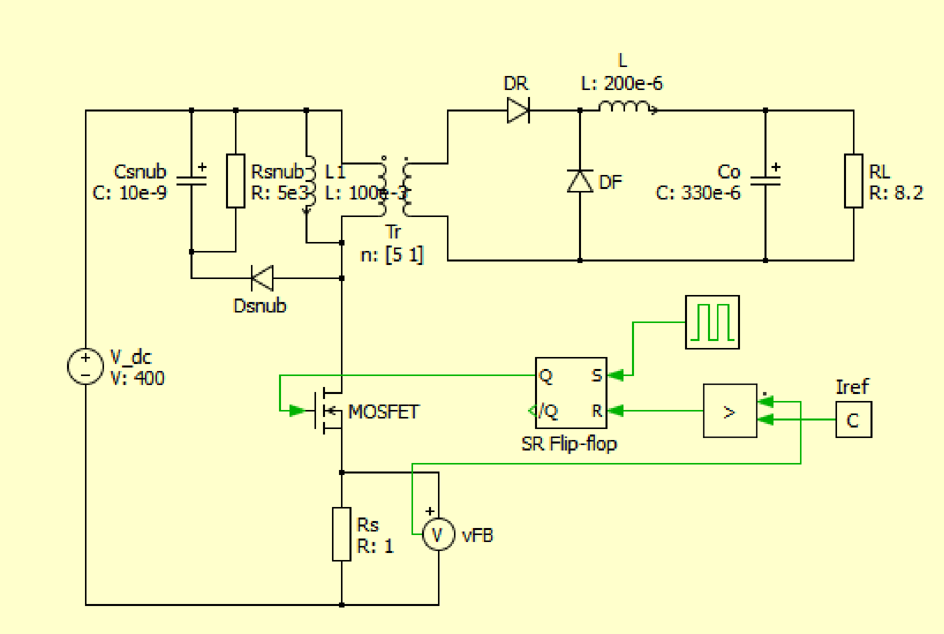


Forward converter switching waveforms

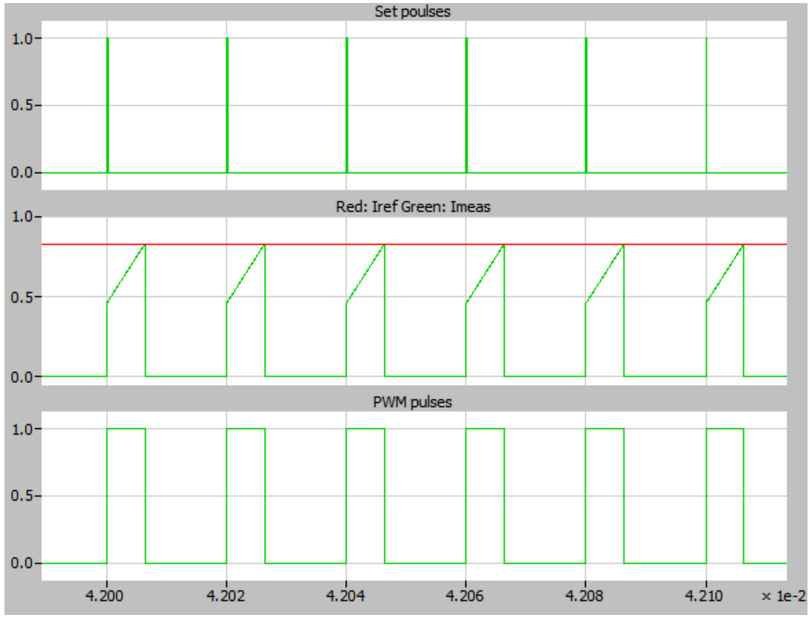




Inner loop - peak current controller



Forward converter with peak current control



Now the current is controlled, we focus on the output voltage!

Voltage control: Control-to-Output function

$$\begin{cases} Ls\hat{i}_L = V_g\hat{d} + D\hat{v}_g - \hat{v}_o \\ Cs\hat{v}_o = \hat{i}_L - \dfrac{\hat{v}_o}{R} \end{cases}$$

$$G_{vd} = \left.\frac{\hat{v}_o}{\hat{d}}\right|_{\hat{v}_g=0}$$

$$G_{vd} = \frac{V_g}{D}\,\frac{\frac{1}{LC}}{s^2 + \frac{1}{CR}s + \frac{1}{LC}}$$

Current control: Control-to-Output function

- Assumption: $i_L = i_c$

$$\begin{cases} Ls\hat{\imath}_c = V_g\hat{d} + D\hat{v}_g - \hat{v}_o \\ Cs\hat{v}_o = \hat{\imath}_c - \dfrac{\hat{v}_o}{R} \end{cases}$$

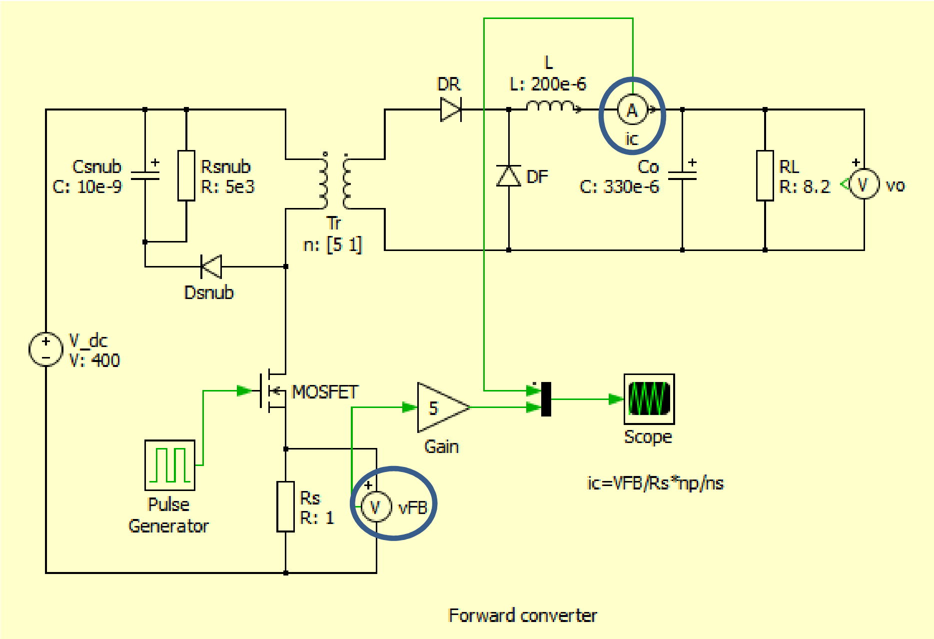
$$G_{vd} = \left.\frac{\hat{v}_o}{\hat{\imath}_c}\right|_{\hat{v}_g=0}$$

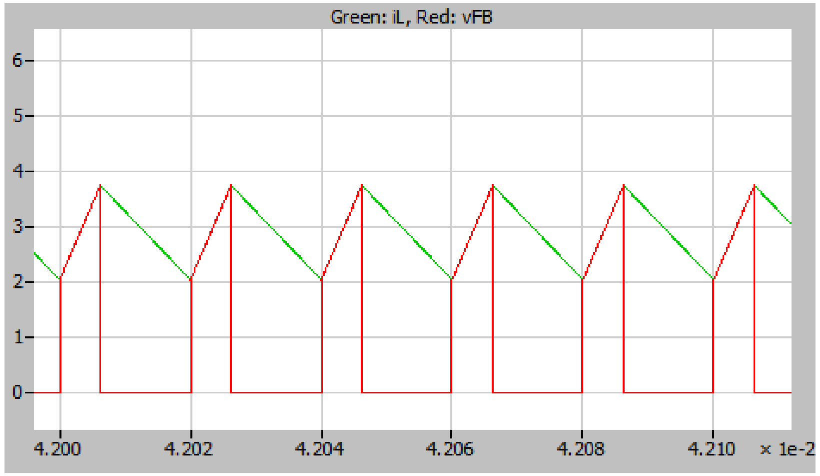
$$G_{vc} = \frac{R}{RCs+1}$$

Control-to-Output function including:

- Transformer turns ratio: n_p/n_s
- Shunt resistor: R_s

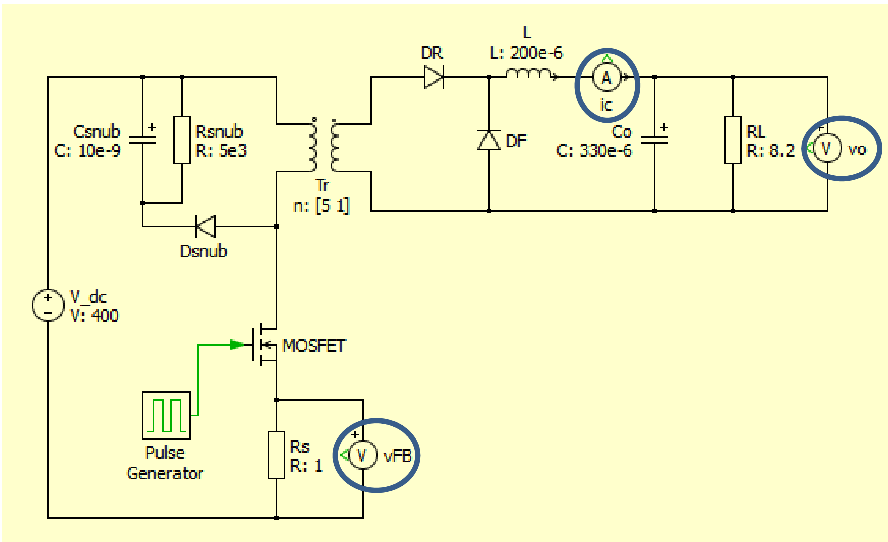
$$G_{cFB} = \frac{\hat{i}_c}{\hat{v}_{FB}} = \frac{1}{R_s}\frac{n_p}{n_s}$$





Control-to-Output function including:

- Transformer turns ratio: n_p/n_s
- Shunt resistor: R_s



Forward converter

$$G_{vc} = \frac{\hat{v}_o}{\hat{\imath}_c} = \frac{R}{RCs+1}$$

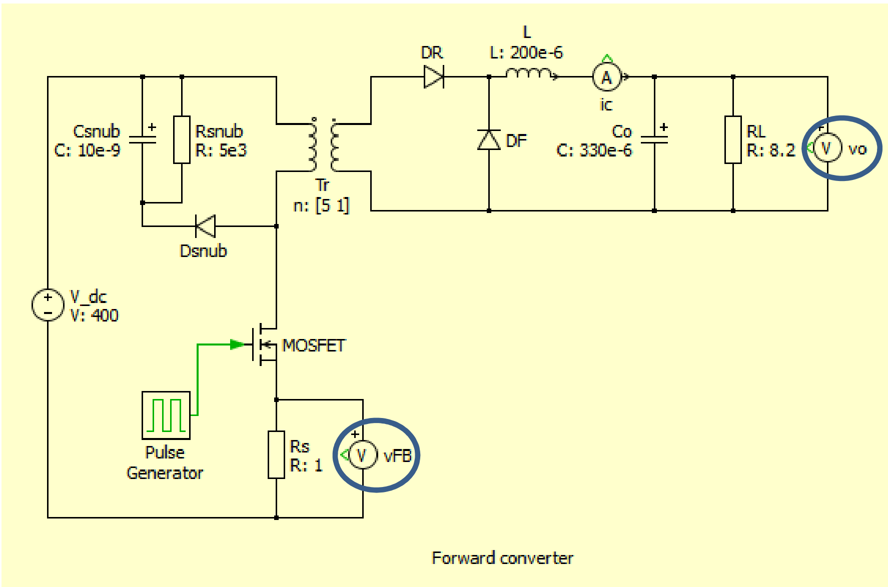
$$G_{cFB} = \frac{\hat{\imath}_c}{\hat{v}_{FB}} = \frac{1}{R_s}\frac{n_p}{n_s}$$

$$G_{vFB} = G_{vc}G_{cFB}$$

Control-to-Output function including:

- Transformer turns ratio: n_p/n_s
- Shunt resistor: R_s

$$G_{vFB} = G_{vc} G_{cFB}$$

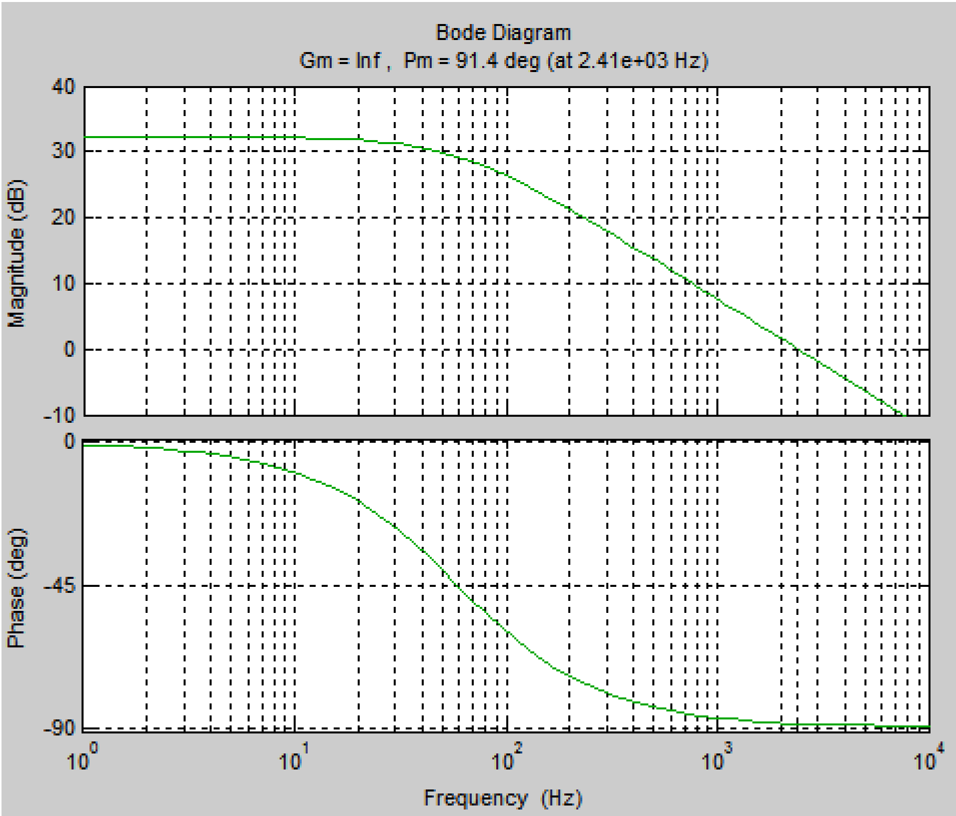


Forward converter

$$G_{vFB} = \frac{\hat{v}_o}{\hat{v}_{FB}} = \frac{1}{R_s} \frac{n_p}{n_s} \frac{R}{RCs+1}$$

Control-to-Output function:

$$G_{vFB} = \frac{\hat{v}_o}{\hat{v}_{FB}} = \frac{1}{R_s}\frac{n_p}{n_s}\frac{R}{RCs+1} = K\frac{1}{\frac{s}{\omega_p}+1}$$



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We need a controller!

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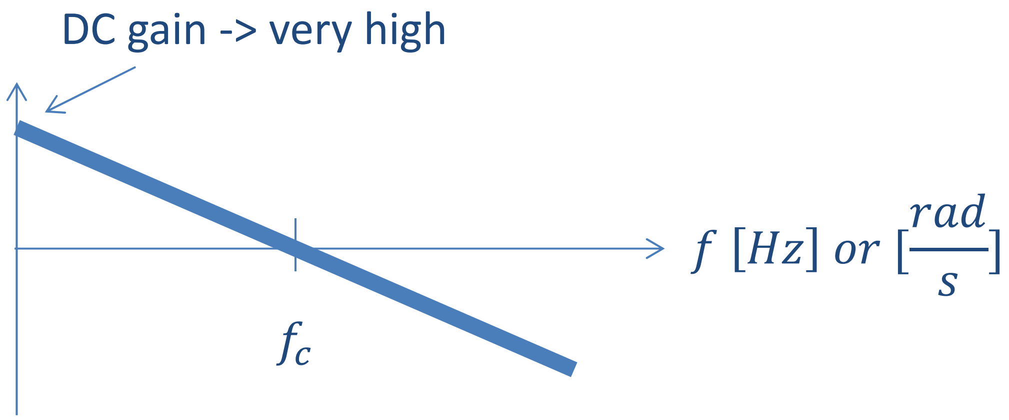
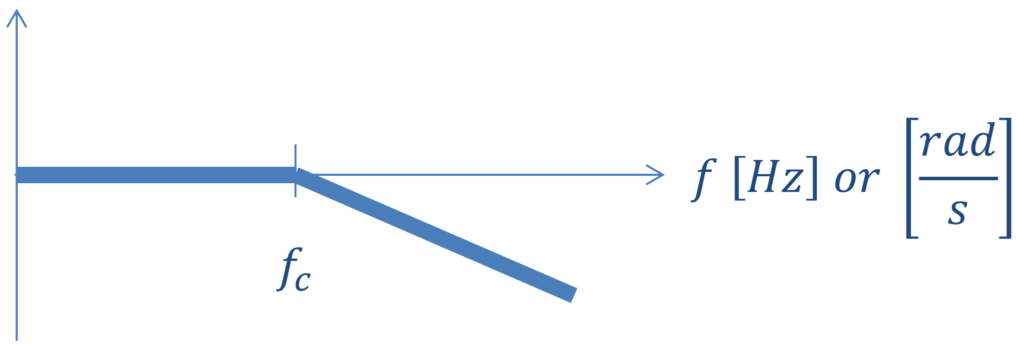
Expected behavior of the controlled system

Open Loop
OL:



Close Loop
CL:



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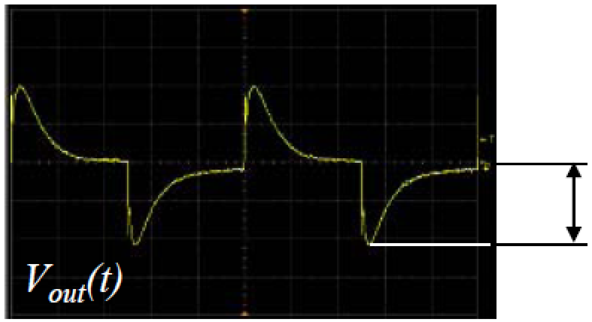
Expected behavior of the controlled system

Which Crossover Frequency to Select?

- 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



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

Source: The TL431 in the Control of Switching Power Supplies

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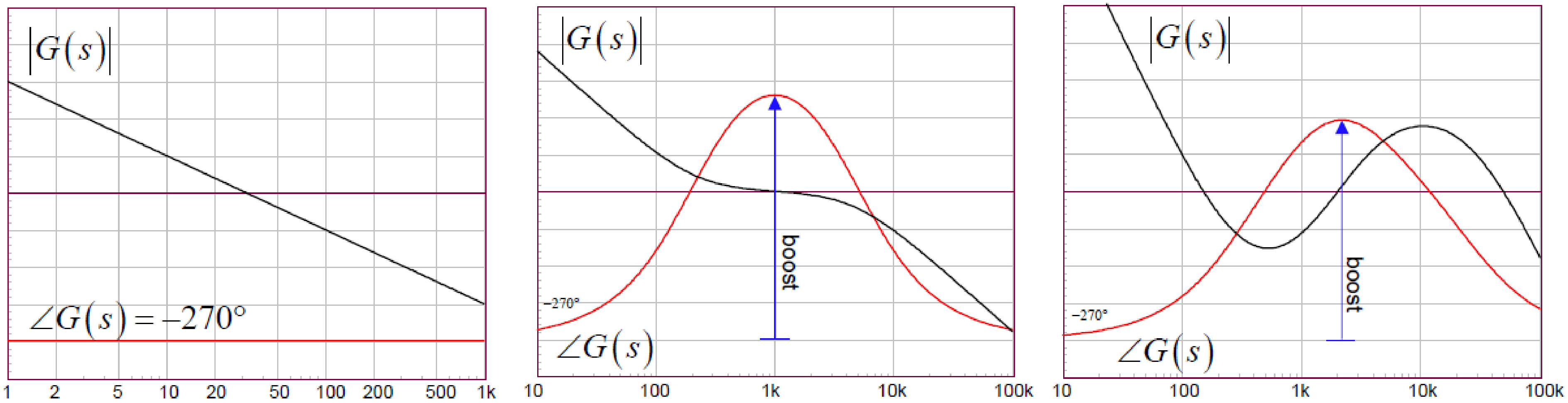
Controller types

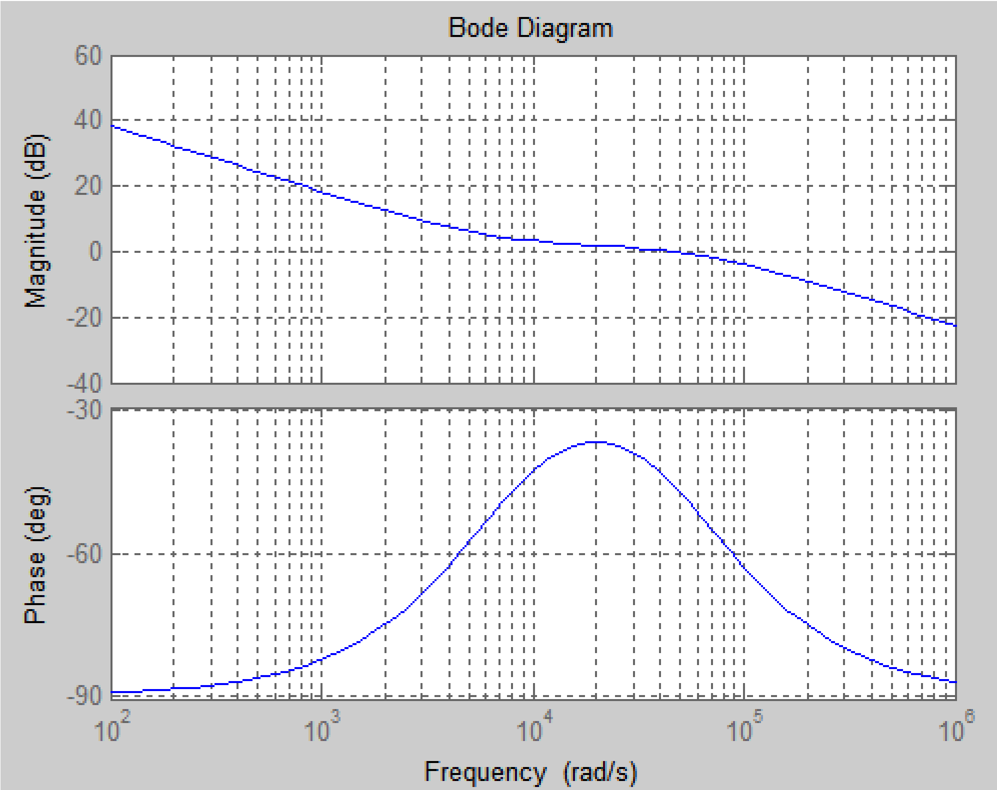
- type 1, 1 pole at the origin, no phase boost
- type 2, 1 pole at the origin, 1 zero, 1 pole. Phase boost up to 90°
- type 3, 1 pole at the origin, 1 zero pair, 1 pole pair. Boost up to 180°



Type 1 Type 2 Type 3

Type II controller

$$G_c = G_0 \cdot \frac{1}{\tau_0 s} \cdot \frac{\tau_{zc} s + 1}{\tau_{pc} s + 1} = G_0 \cdot \frac{1}{\frac{s}{\omega_0}} \cdot \frac{\frac{s}{\omega_{zc}} + 1}{\frac{s}{\omega_{pc}} + 1}$$



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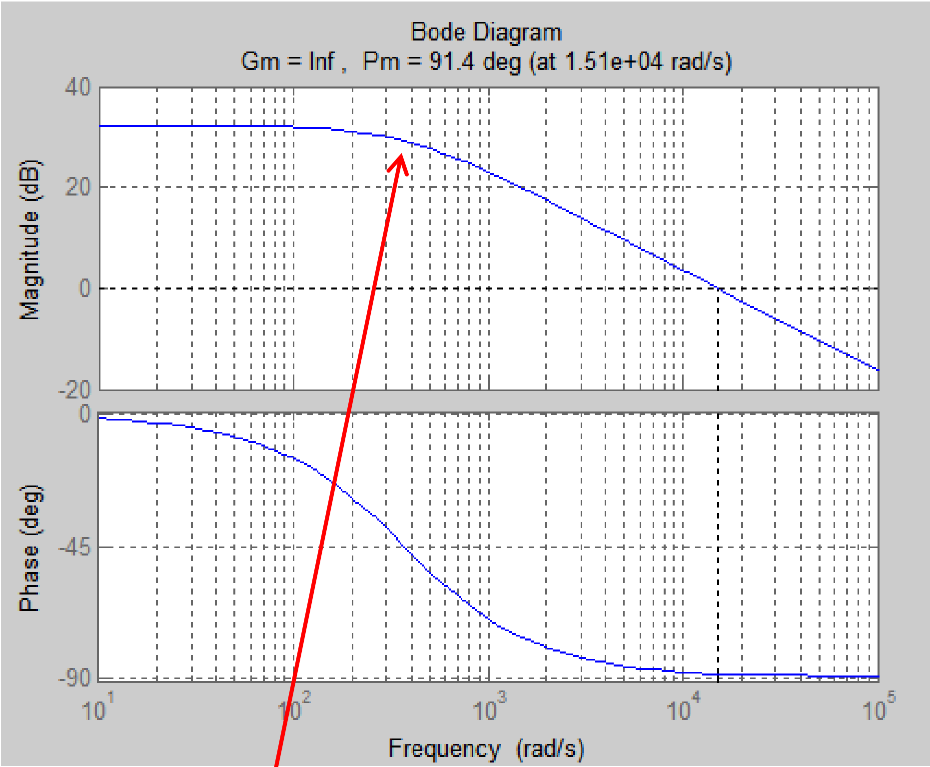
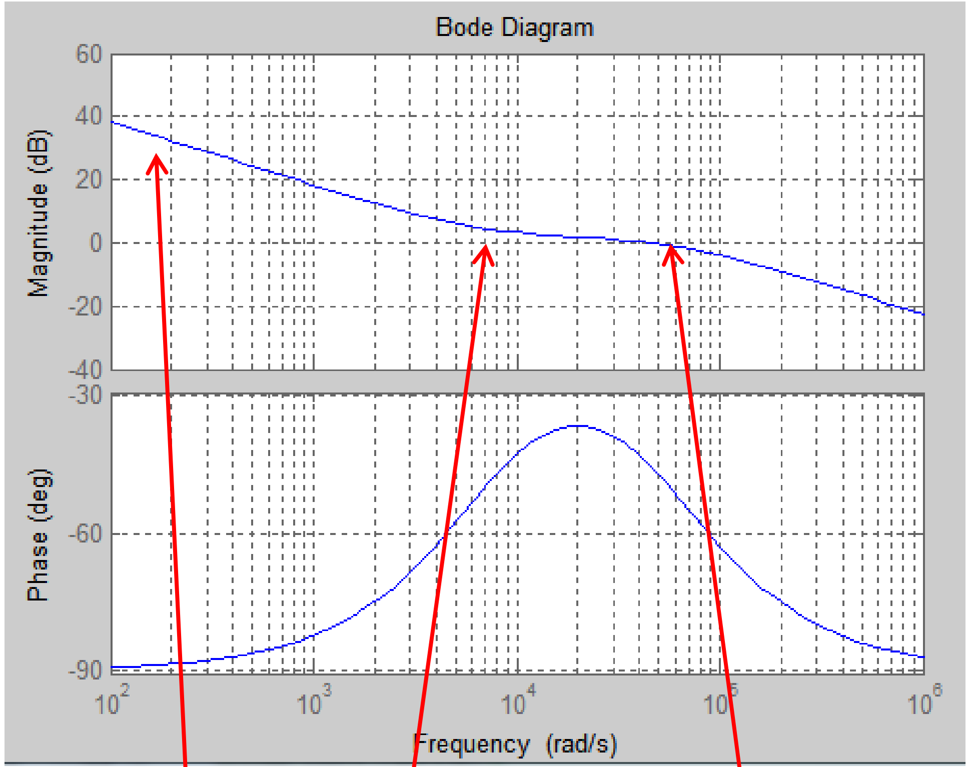
Why Type II controller?

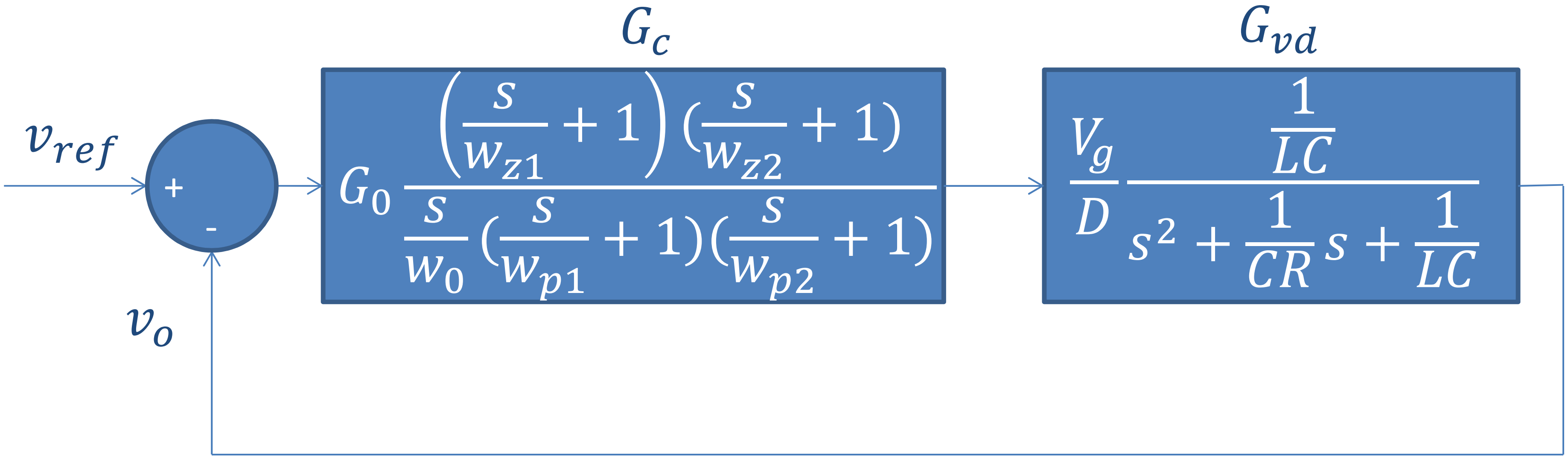




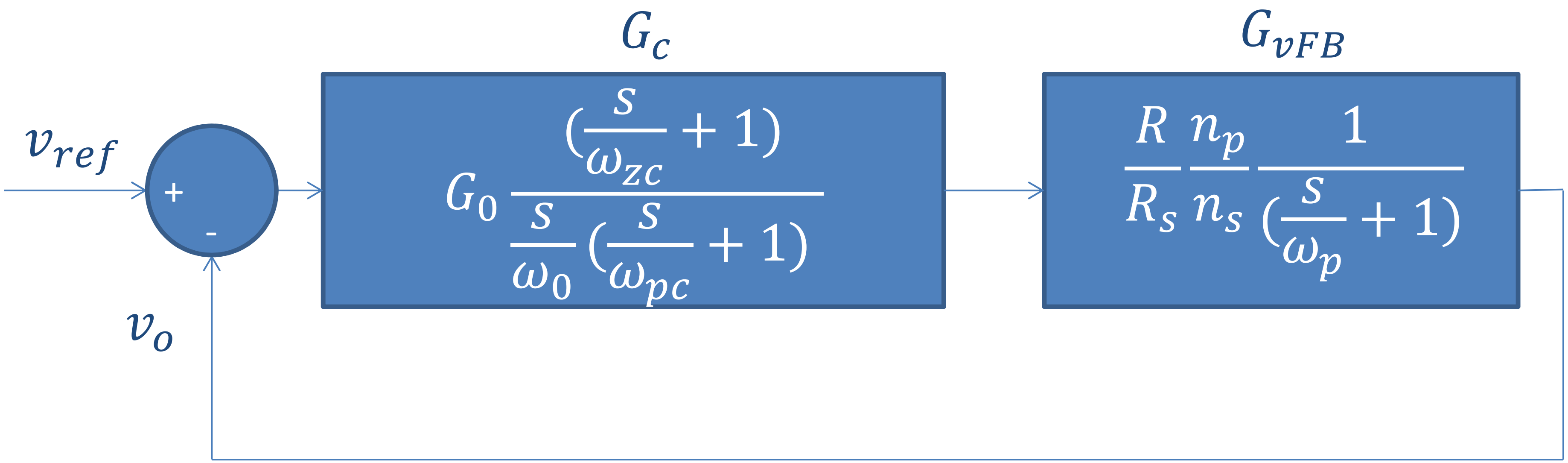
$$\frac{1}{R_S}\frac{n_p}{n_s}\frac{1}{\frac{s}{\omega_p}+1}$$

$$\frac{1}{\frac{s}{\omega_0}} \qquad \frac{s}{\omega_{zc}}+1 \qquad \frac{s}{\omega_{pc}}+1$$

Control structure – voltage mode



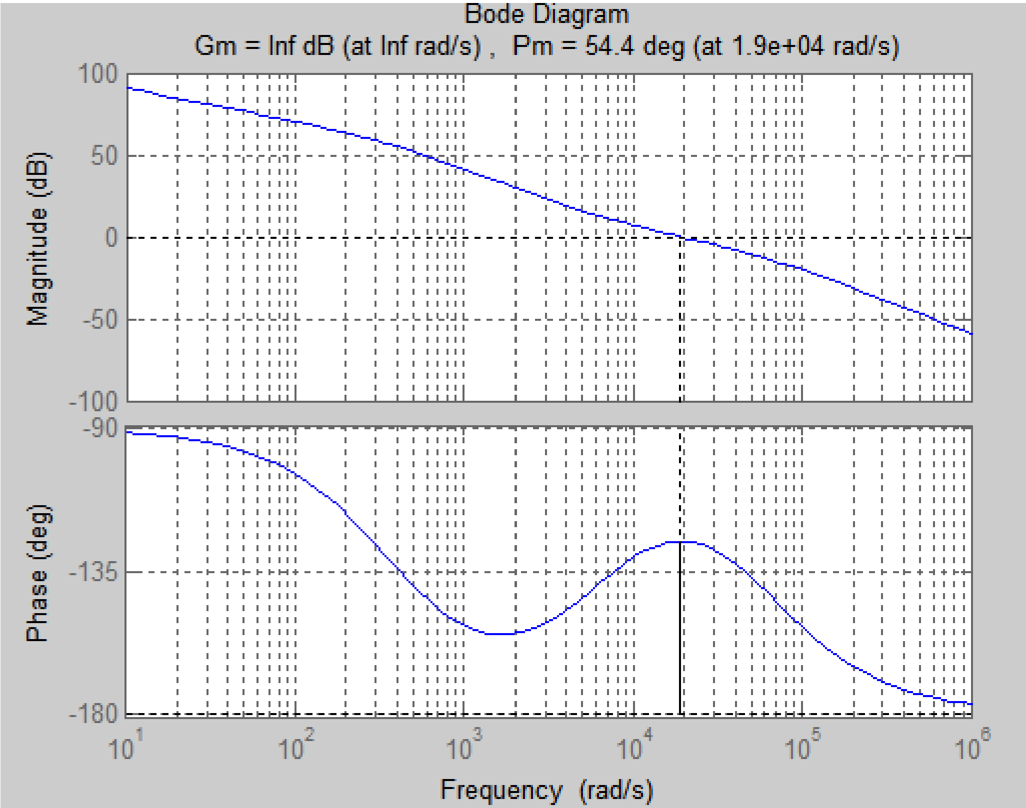
Control structure – current mode



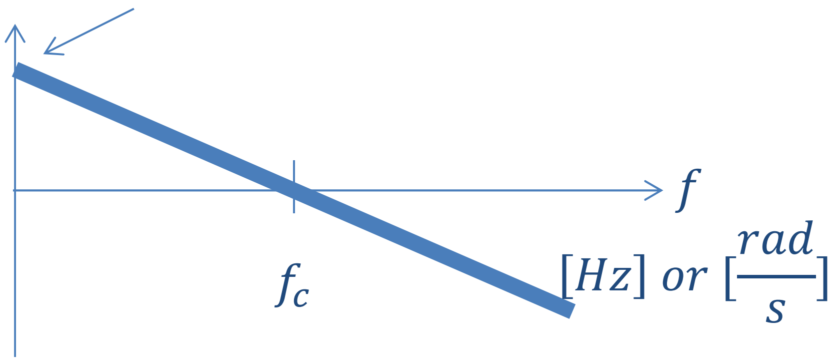
Open loop gain – $T_{OL}(s)$

$$T_{OL}(s) = G_C(s) \cdot G_{vFB}(s)$$

$$G_{CL}(s) = \frac{T_{OL}(s)}{1 + T_{OL}(S)}$$



DC gain -> very high



Notice : T_{ol} – strongly depend on load - R

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Implementation

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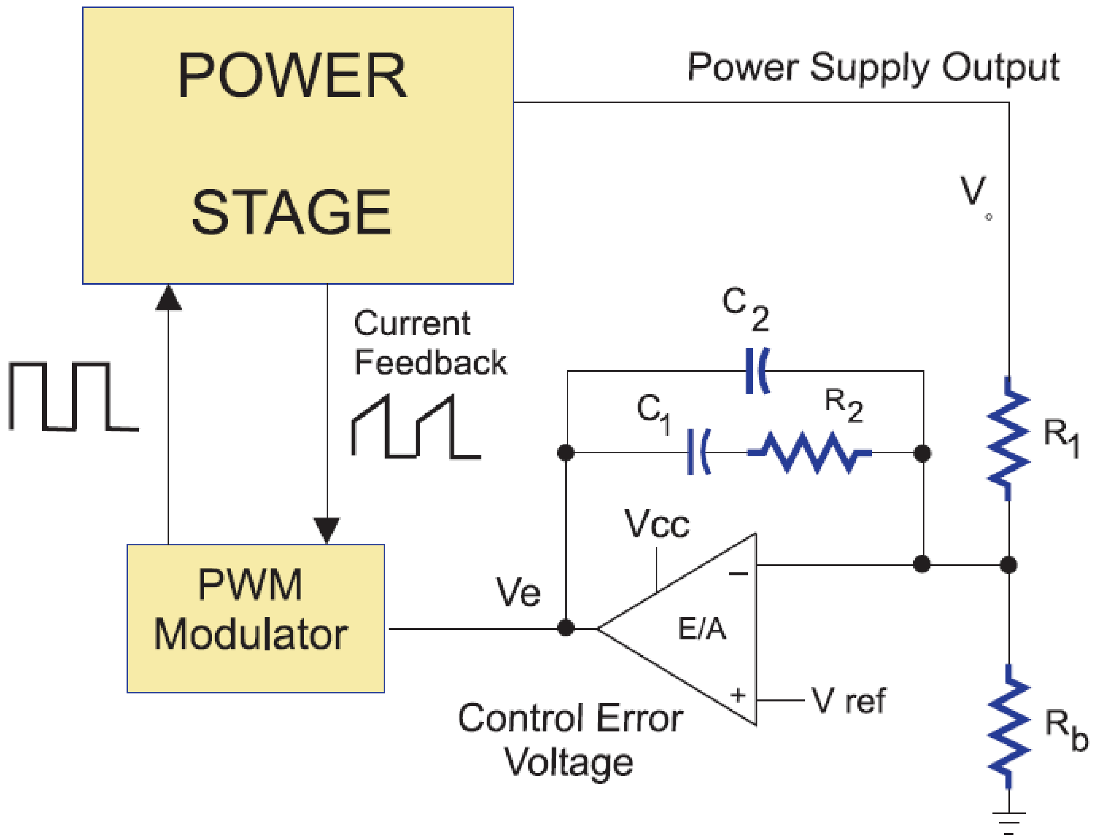
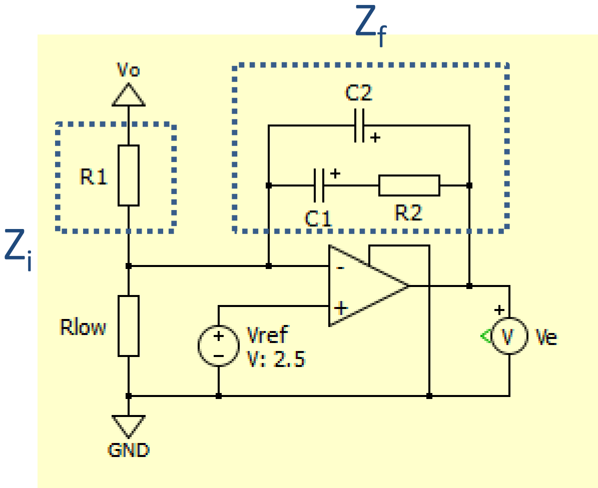
Implementation with operational amplifier



*Type II Compensation Feedback using Operational Amplifier**

Reference picture: Designing with the TL431* ***by Dr. Ray Ridley, Designer Series XV*

Implementation with operational amplifier



$$G_C(s) = \frac{v_e}{v_o} = \frac{Z_f}{Z_i} = G_0 \cdot \frac{1}{\frac{s}{\omega_0}} \cdot \frac{\frac{s}{\omega_{zc}} + 1}{\frac{s}{\omega_{pc}} + 1}$$

$$\omega_0 = \frac{1}{R_1 C_1}; \omega_{zc} = \frac{1}{R_2 C_1}; \omega_{pc} = \frac{1}{R_2 C_2}$$

- Valid if $C_2 << C_1$

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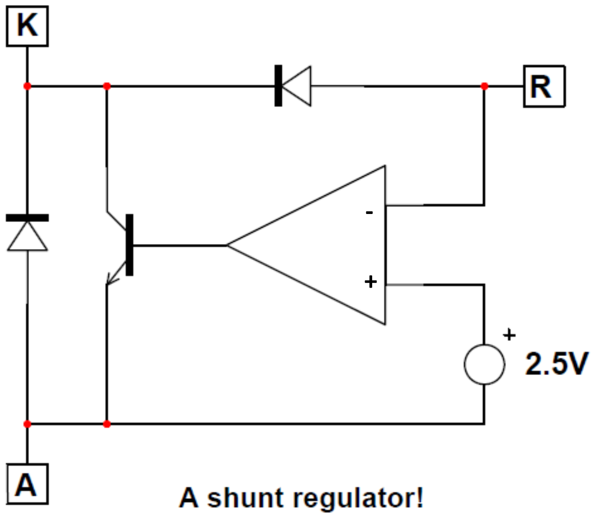
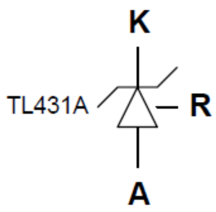
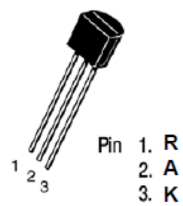
Implementation with TL431

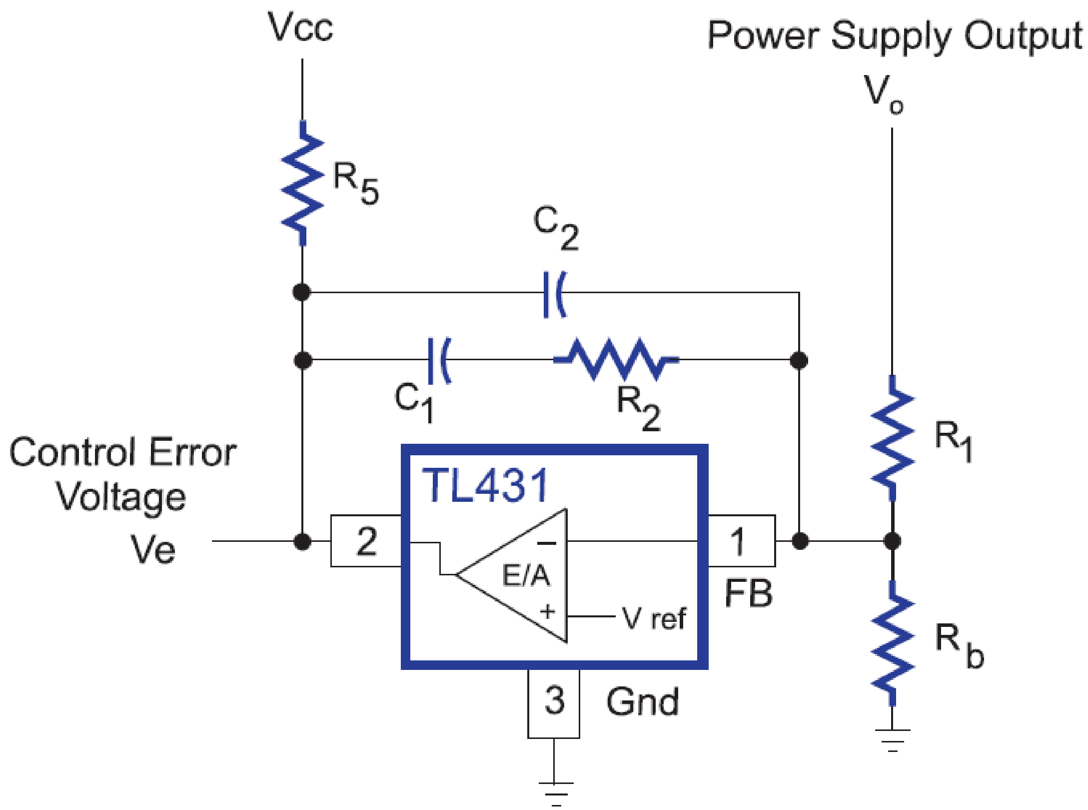


A shunt regulator!





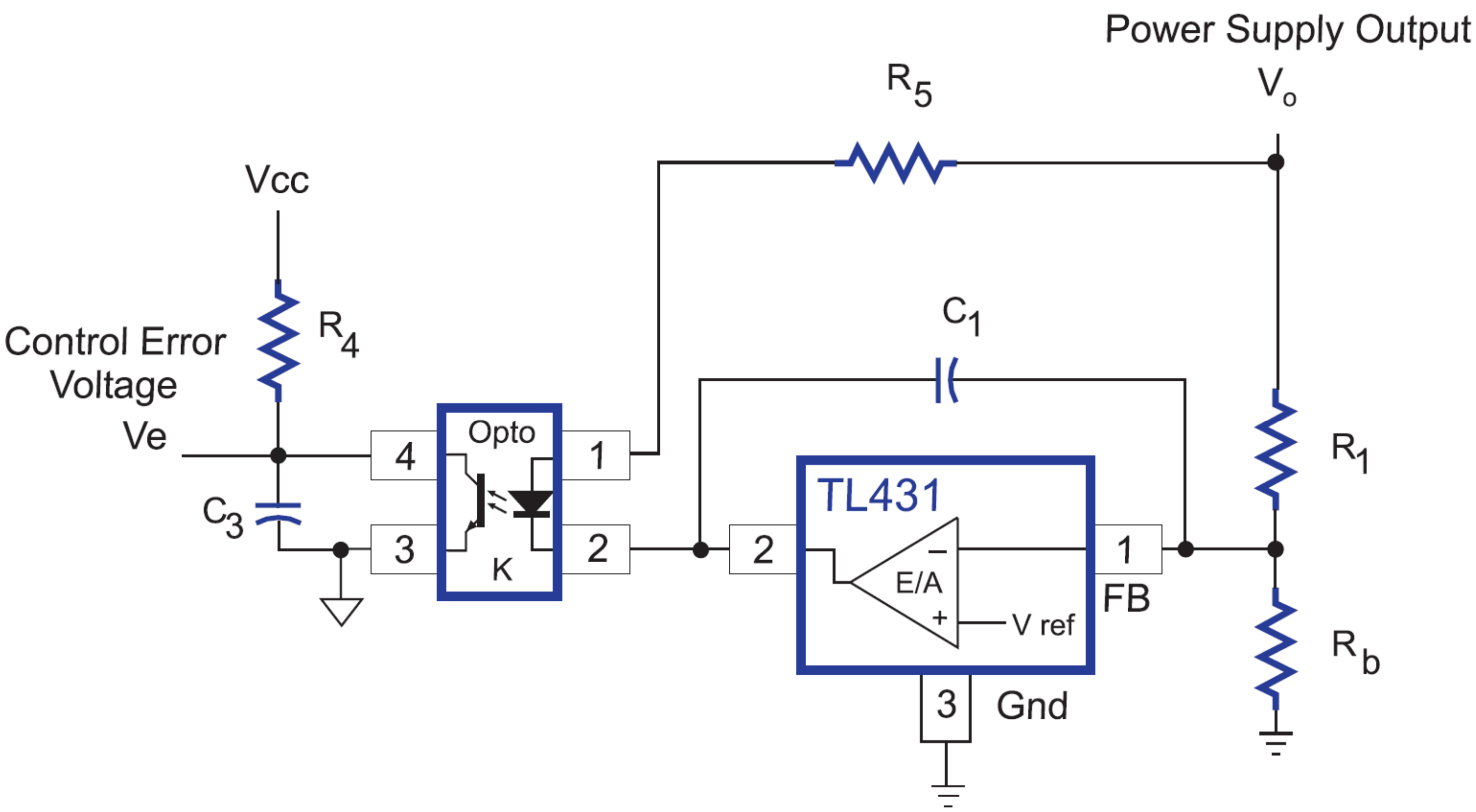
Implementation with TL431



*Type II Compensation Feedback using TL431**

Reference picture: Designing with the TL431* ***by Dr. Ray Ridley, Designer Series XV*

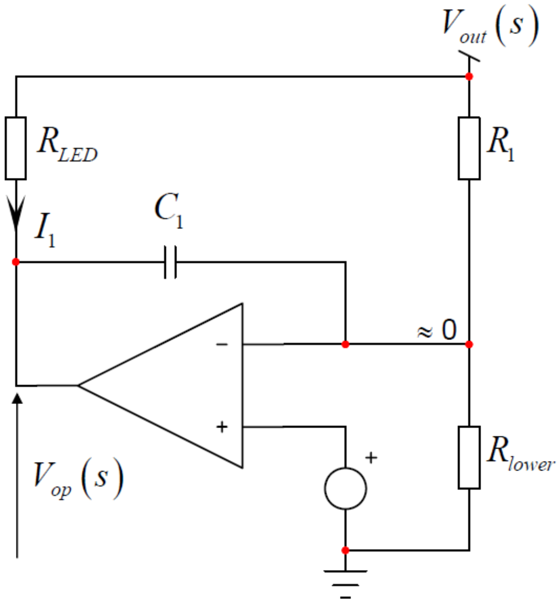
Implementation with TL431 and optocoupler



*Type II Compensation Feedback using TL431 and optocoupler**

Reference picture: Designing with the TL431* ***by Dr. Ray Ridley, Designer Series XV*

Implementation with TL431 and optocoupler



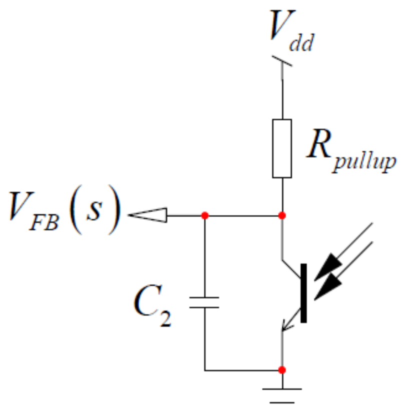
$$I_1(s) = \frac{V_{out}(s) - V_{op}(s)}{R_{LED}}$$

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

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

We know that: $V_{FB}(s) = -\mathrm{CTR} \cdot R_{pullup} \cdot I_1$

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



Add a cap. from collector to ground

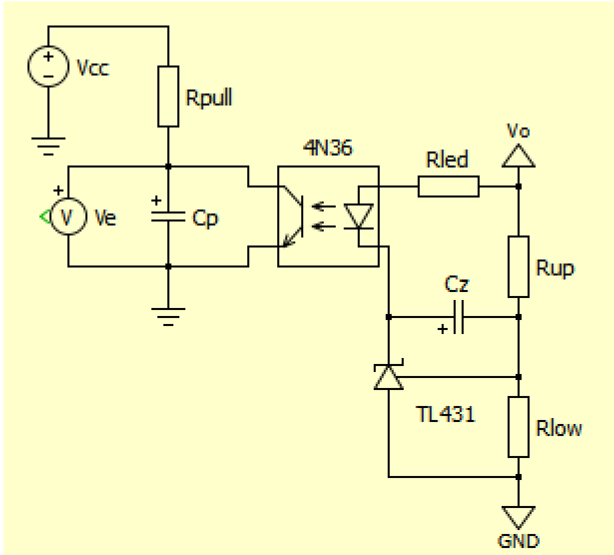
Type 2 transfer function

$$\frac{V_{FB}(s)}{V_{out}(s)} = -\underbrace{\frac{R_{pullup}\mathrm{CTR}}{R_{LED}}\left[\frac{1 + sR_{upper}C_1}{sR_{upper}C_1\left(1 + sR_{pullup}C_2\right)}\right]}_{\text{Type 2 transfer function}}$$

Implementation with TL431 and optocoupler

$$G_C(s) = \frac{v_e}{v_o} = G_0 \cdot \frac{1}{\frac{s}{\omega_0}} \cdot \frac{\frac{s}{\omega_{zc}} + 1}{\frac{s}{\omega_{pc}} + 1}$$

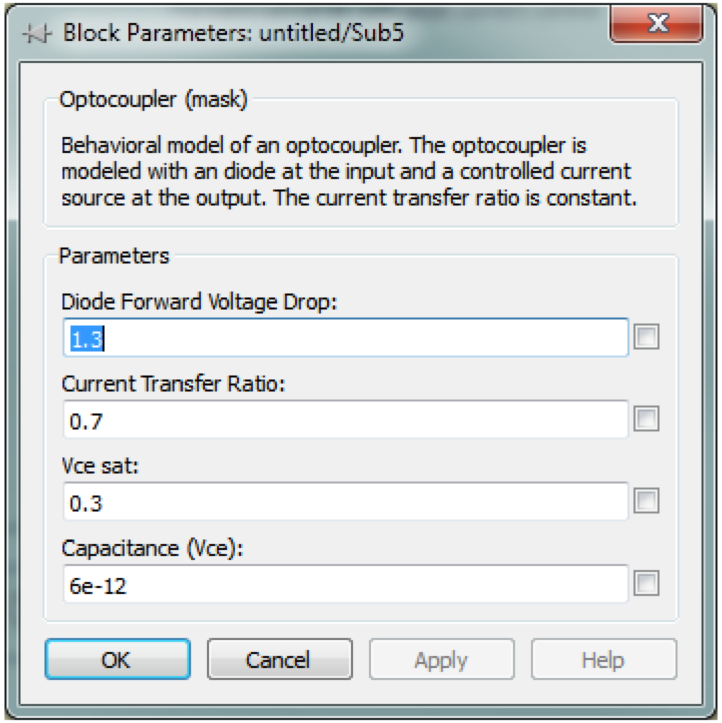
$$G_0 = \frac{R_{pull} CTR}{R_{led}}; \omega_0 = \frac{1}{R_{up} C_z}; \omega_{zc} = \frac{1}{R_{up} C_z}; \omega_{pc} = \frac{1}{R_{pull} C_p}$$

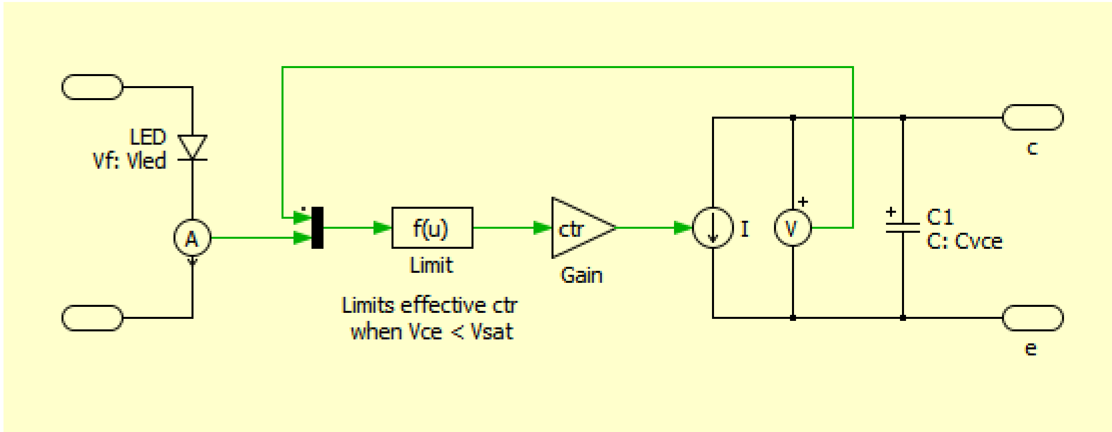


Notice : CTR – Current Transfer Ratio of the optocoupler, it can be found in a datasheet:
Ex. http://www.vishay.com/docs/81181/4n35.pdf

Also useful information about a real TL431 you can find from a datasheet:
Ex. http://www.ti.com/lit/ds/symlink/tl431.pdf

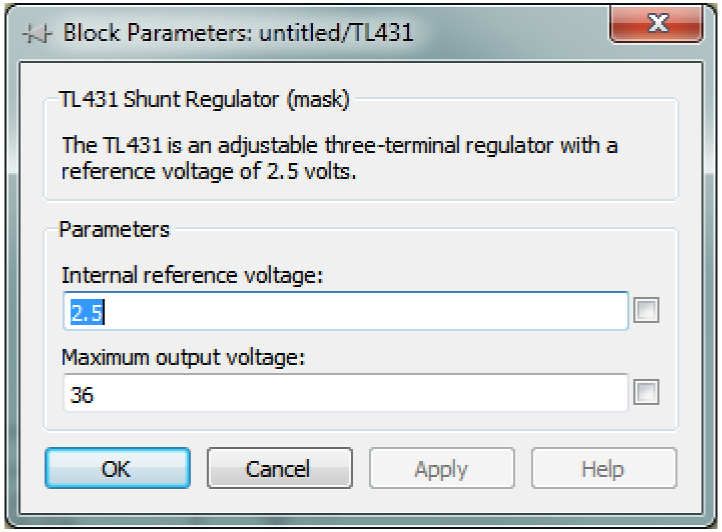
Optocoupler model

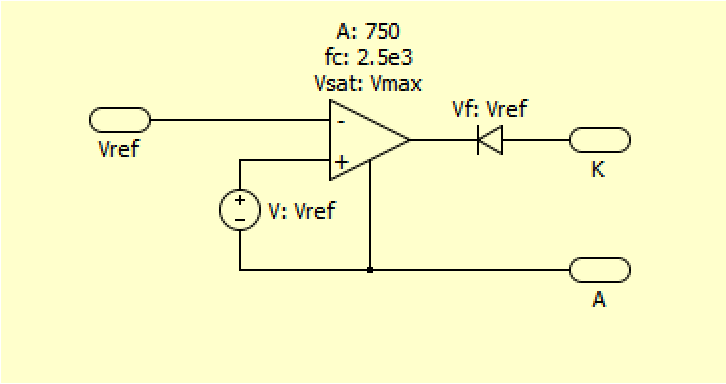




Model of the optocoupler in PLECS

TL431 model

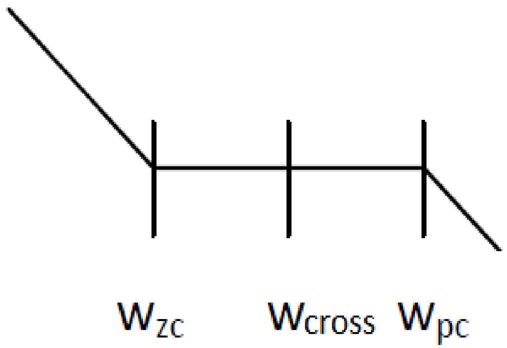




Model of the TL431 in PLECS

Technical issues

Determine the w_z and the w_p



$$w_{cross} = \sqrt{w_{cz} w_{cp}}$$

Determine the $||G_c(w_{cross})||$ ($s = jw_{cross}$)

$$G_C(\omega_{cross}) = G_0 \frac{\omega_0}{j\sqrt{\omega_{cz}\omega_{cp}}} \frac{1 + j\sqrt{\frac{\omega_{cp}}{\omega_{cz}}}}{1 + j\sqrt{\frac{\omega_{cz}}{\omega_{cp}}}}$$

$$\|G_C(\omega_{cross})\| = G_0 \frac{\omega_0}{\sqrt{\omega_{cz}\omega_{cp}}} \frac{\sqrt{1 + \frac{\omega_{cp}}{\omega_{cz}}}}{\sqrt{1 + \frac{\omega_{cz}}{\omega_{cp}}}}$$

$$\|G_C(\omega_{cross})\|_{dB} = -\|G_{vFB}(\omega_{cross})\|_{dB}$$

$$\|G_C(\omega_{cross})\|_{mag} = G_0 = \frac{R_{pull} CTR}{R_{led}}$$

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Technical issues

Calculating R_{led}

$$R_{led} = (\mathrm{V_o} - \mathrm{V_F} - \mathrm{V_K}) / i_F$$

Obtaining CTR

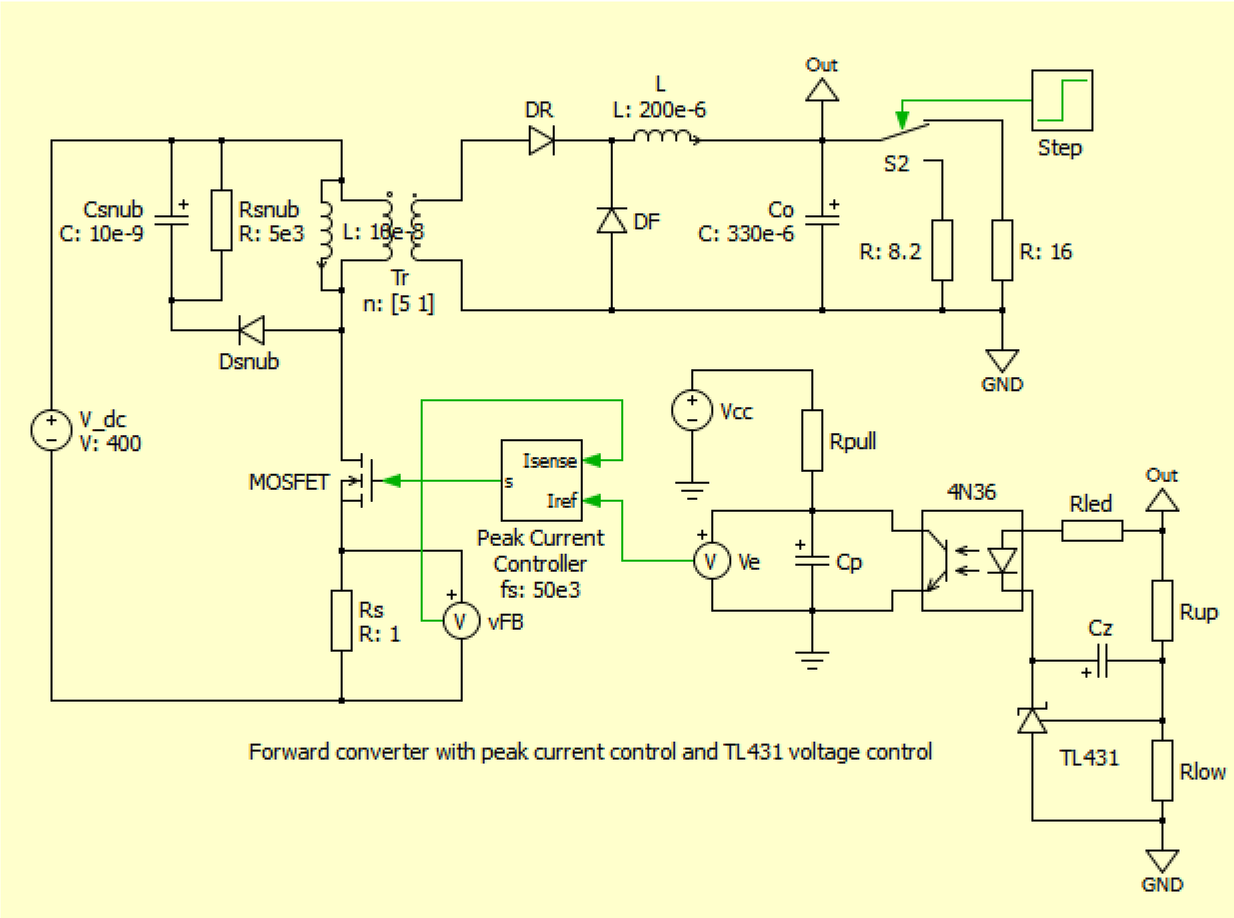
$$CTR = Gain = \frac{i_C}{i_F}$$

i_c = transistor collector current and i_F is diode current (see datasheet)

Finding R_{up} and R_{low}

$$2.5V = 24V \frac{R_{low}}{R_{up} + R_{low}}$$

Simulations



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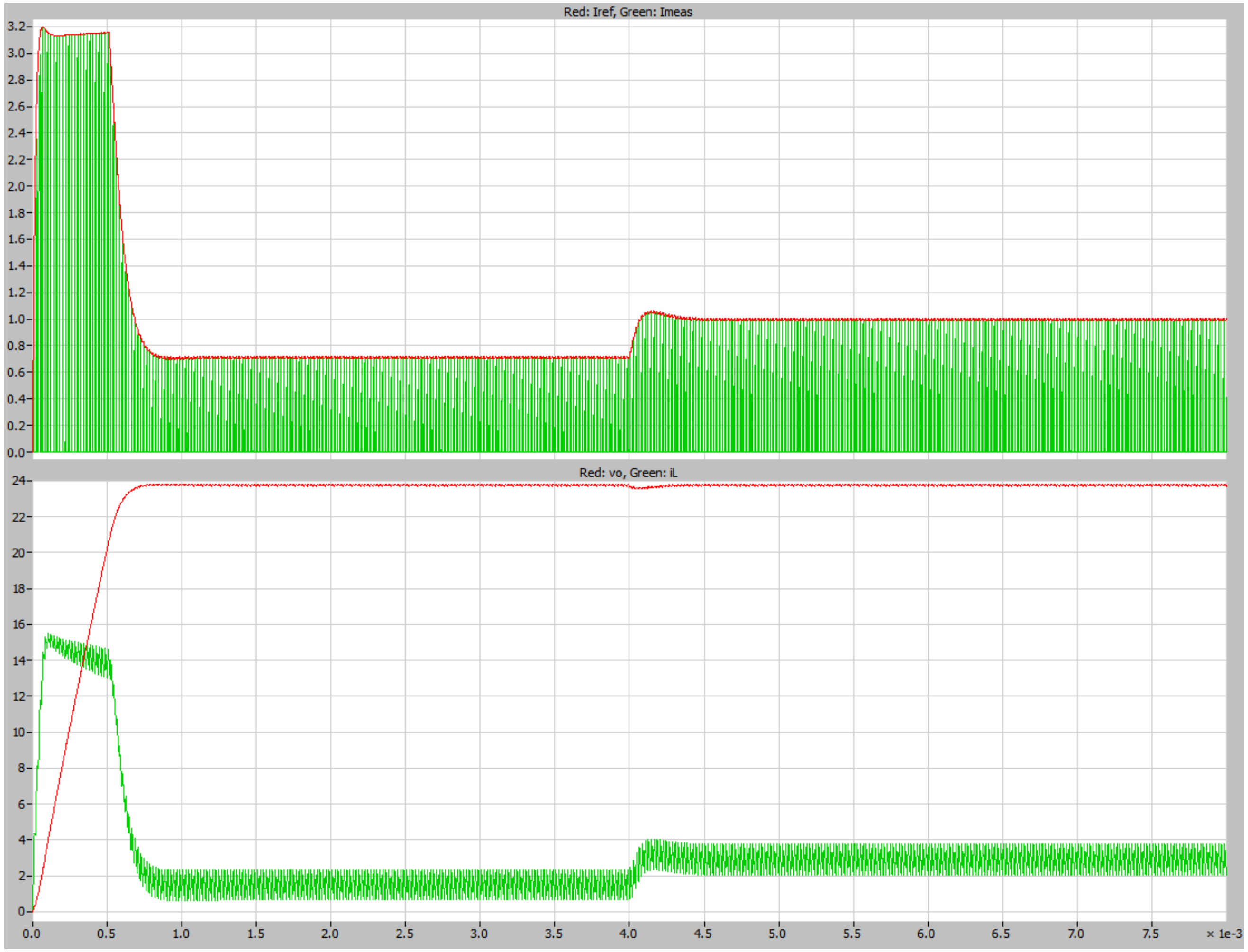
Simulations



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Exercise:

Given is a forward converter model in PLECS (see Starting Model.plecs file)

- The converter has v_o=24V and it delivers 70W power.
- Switching frequency should be 50 kHz
- $n_p/n_s = 5$
- Desired crossover frequency: $\omega_{cross} = 20000 \frac{rad}{s}$

Task: Design a control structure for the converter using the peak current controller, the TL431 and the optocoupler blocks – similarly to the one presented during the course.

0: Using the formulas given in the lecture, sketch the bode plot of $G_{vFB}(s)$ in Matlab. Also use Matlab for checking your controller's behavior on its bode plots.
1: Select the values for R_{up} and R_{low}
2: Find the desired gain at w_{cross} ($G_0=CTR*R_{pull}/R_{led}$)
3: Find $w_{zc} = w_{cross} / 3$; select C_z
4: Find $w_{pc} = w_{cross} * 3$; select C_p , R_{pull} and R_{led}
See next page for 5: ☺

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Exercise:

5: Simulate in PLECS:

a. Test power circuit in open loop and see waveforms
b. Build current controller
c. Build TL431 control circuit
d. Simulate the converter in closed loop and plot the T_{ol} as well.

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