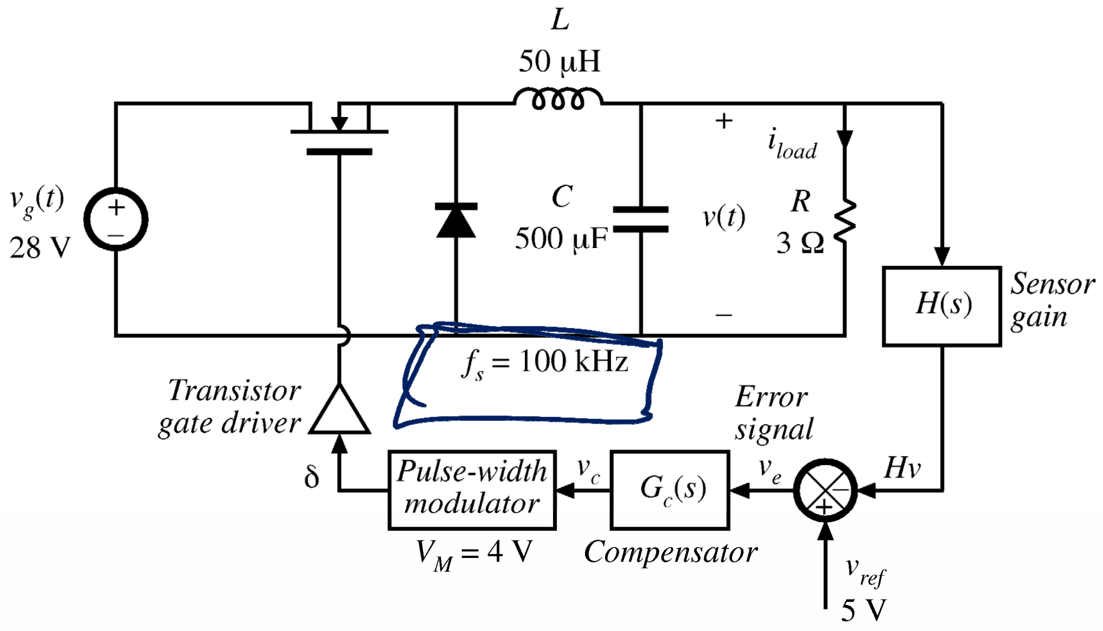
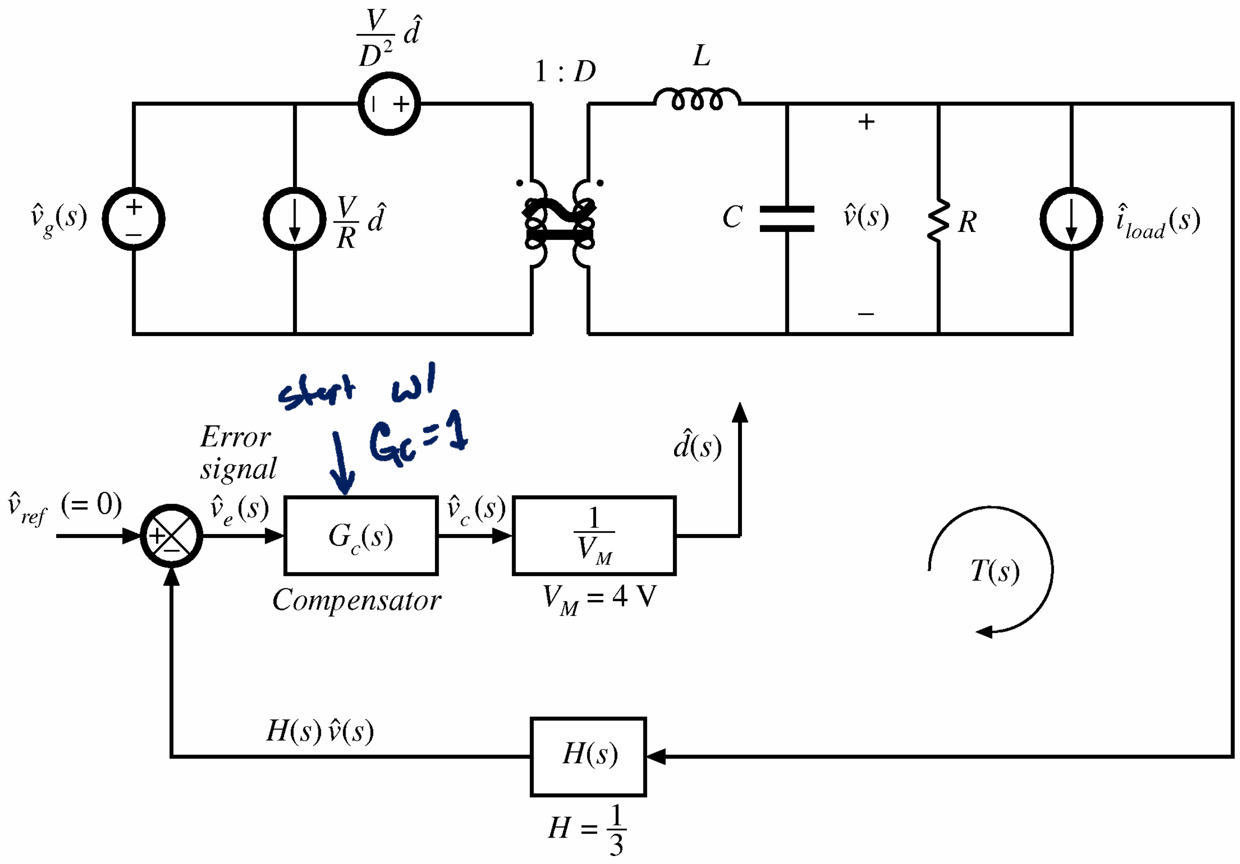
Example Design of Buck Compensator



Input voltage	$V_g = 28\text{V}$
Output	$V = 15\text{V}$, $I_{load} = 5\text{A}$, $R = 3\Omega$
Quiescent duty cycle	$D = 15/28 = 0.536$
Reference voltage	$V_{ref} = 5\text{V}$
Quiescent value of control voltage	$V_c = DV_M = 2.14\text{V}$
Gain $H(s)$	$H = V_{ref}/V = 5/15 = 1/3$

AC Power Stage Model

Table 7.1



start w/

$G_c = 1$

System Block Diagram

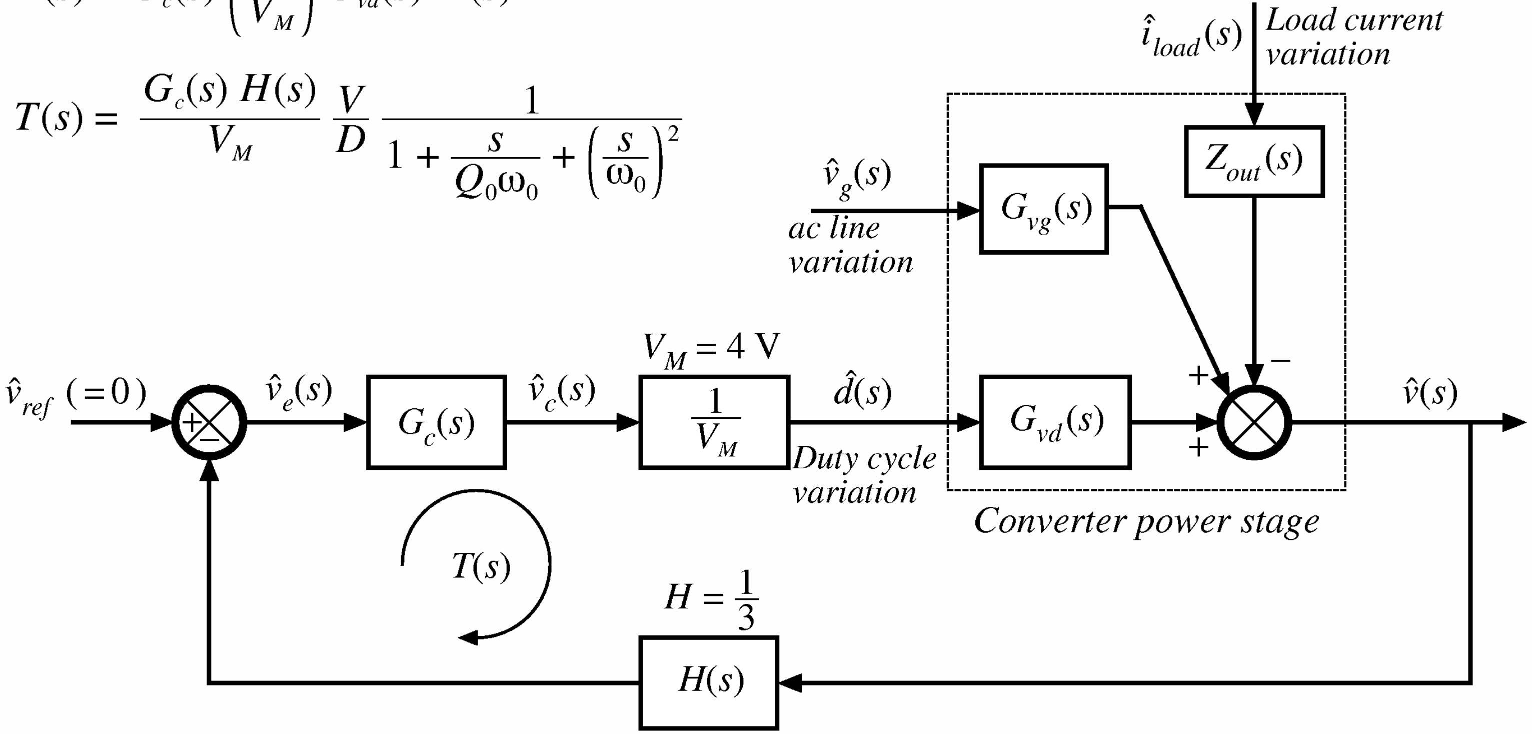
$$\hat{v} = \frac{1}{H}\frac{T}{1+T}\hat{v}_{ref} + \frac{1}{1+T}G_{vg}\hat{v}_g - \frac{1}{1+T}Z_{out}\hat{i}_{load}$$

"Uncompensated loop Gain"

$$T_u(s) = \underset{\uparrow}{1} \cdot \frac{1}{V_M} G_{vd}(s)\, H(s)$$

$$T(s) = G_c(s)\left(\frac{1}{V_M}\right) G_{vd}(s)\, H(s)$$

$$T(s) = \frac{G_c(s)\, H(s)}{V_M}\,\frac{V}{D}\,\frac{1}{1 + \frac{s}{Q_0\omega_0} + \left(\frac{s}{\omega_0}\right)^2}$$



Plotting Uncompensated Loop Gain

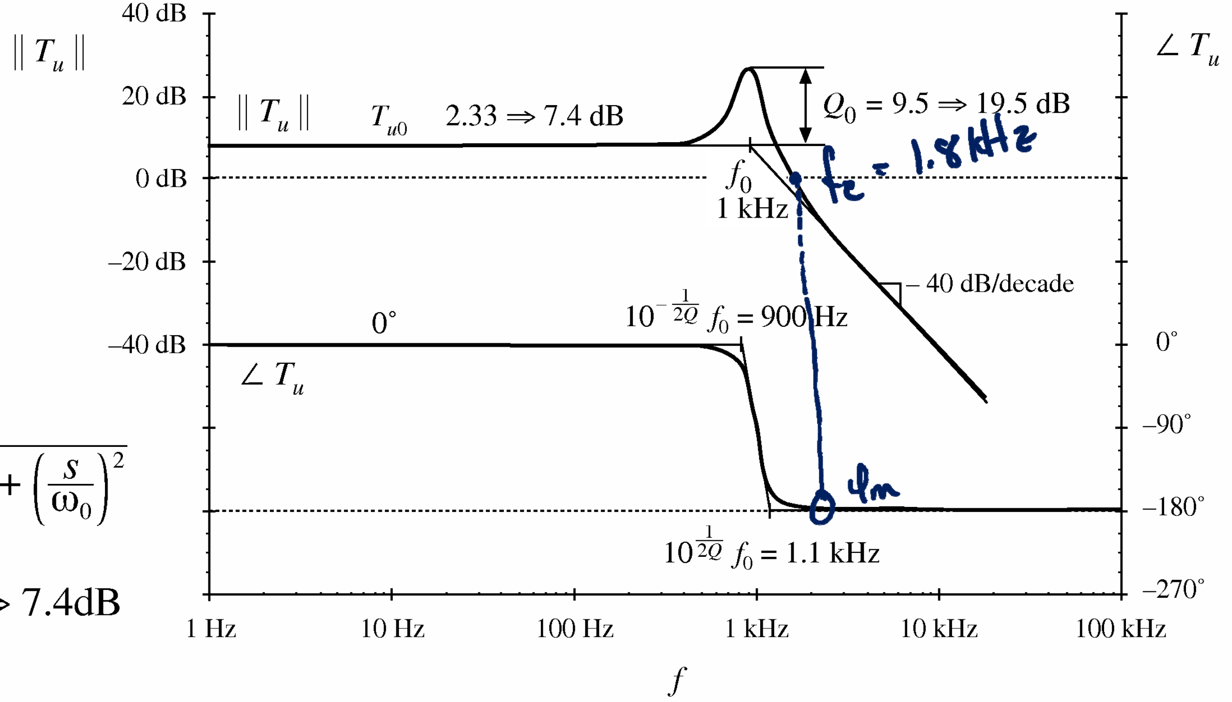
(1) $T(0)$ is too small → will have significant steady-state error

(2) $\varphi_m = 5^\circ$ is too small → lots of ringing / overshoot & risk of instability

(3) $f_c = 1.8$ kHz ≈ ok

can push further to

$\frac{f_s}{10} = 10$ kHz



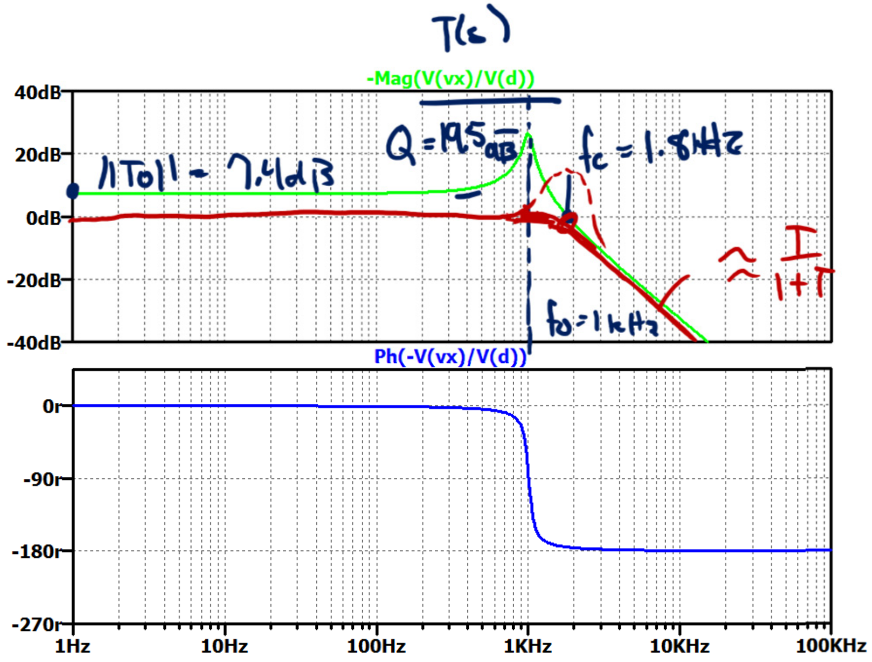
With $G_c = 1$, the loop gain is

$$T_u(s) = T_{u0} \frac{1}{1 + \frac{s}{Q_0 \omega_0} + \left(\frac{s}{\omega_0}\right)^2}$$

$$T_{u0} = \frac{H\,V}{D\,V_M} = 2.33 \Rightarrow 7.4\text{dB}$$

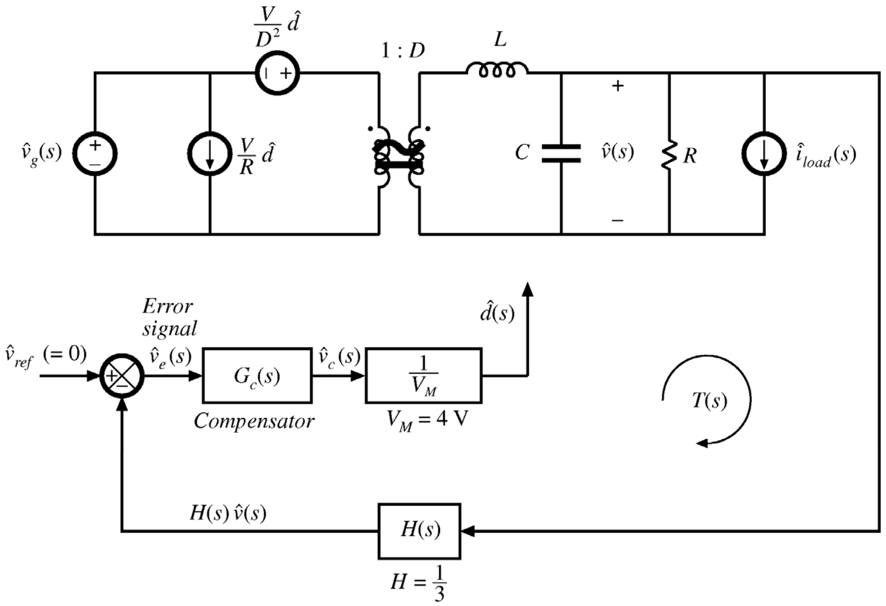
$f_c = 1.8$ kHz, $\varphi_m = 5^\circ$

LTSpice Simulation – AC, Uncompensated



```
.lib myParts.lib
.ac dec 1000 1 1Meg
```

```
.param Vg = 28  V = 15  R = 3  D = .536
.param Vref = 5  H = 1/3  Vm = 4
.param L = 50u C = 500u
```



LTSpice ac Simulations

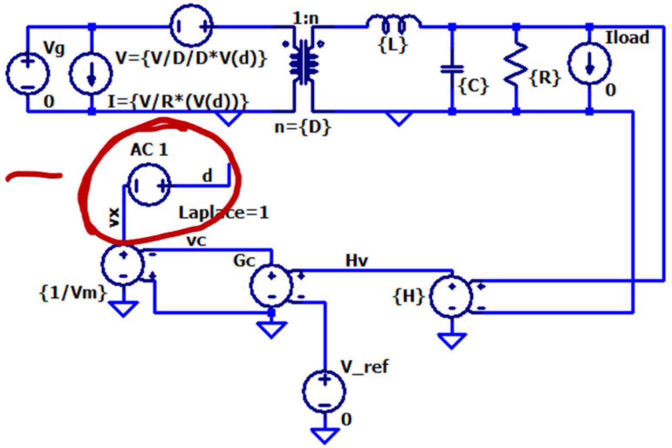
usually, run a .op first to make sure LTSpice finds the correct operating point, then run .ac

$T = -\frac{V(vx)}{V(d)}$

Averaged, linearized

.lib myParts.lib
.ac dec 1000 1 1Meg

.param Vg = 28 V = 15 R = 3 D = .536
.param Vref = 5 H = 1/3 Vm = 4
.param L = 50u C = 500u

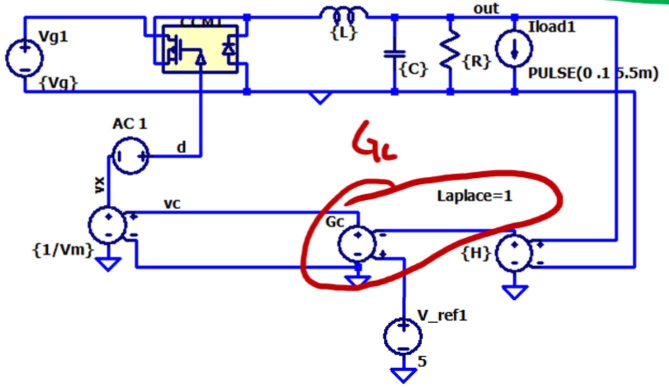


Averaged model

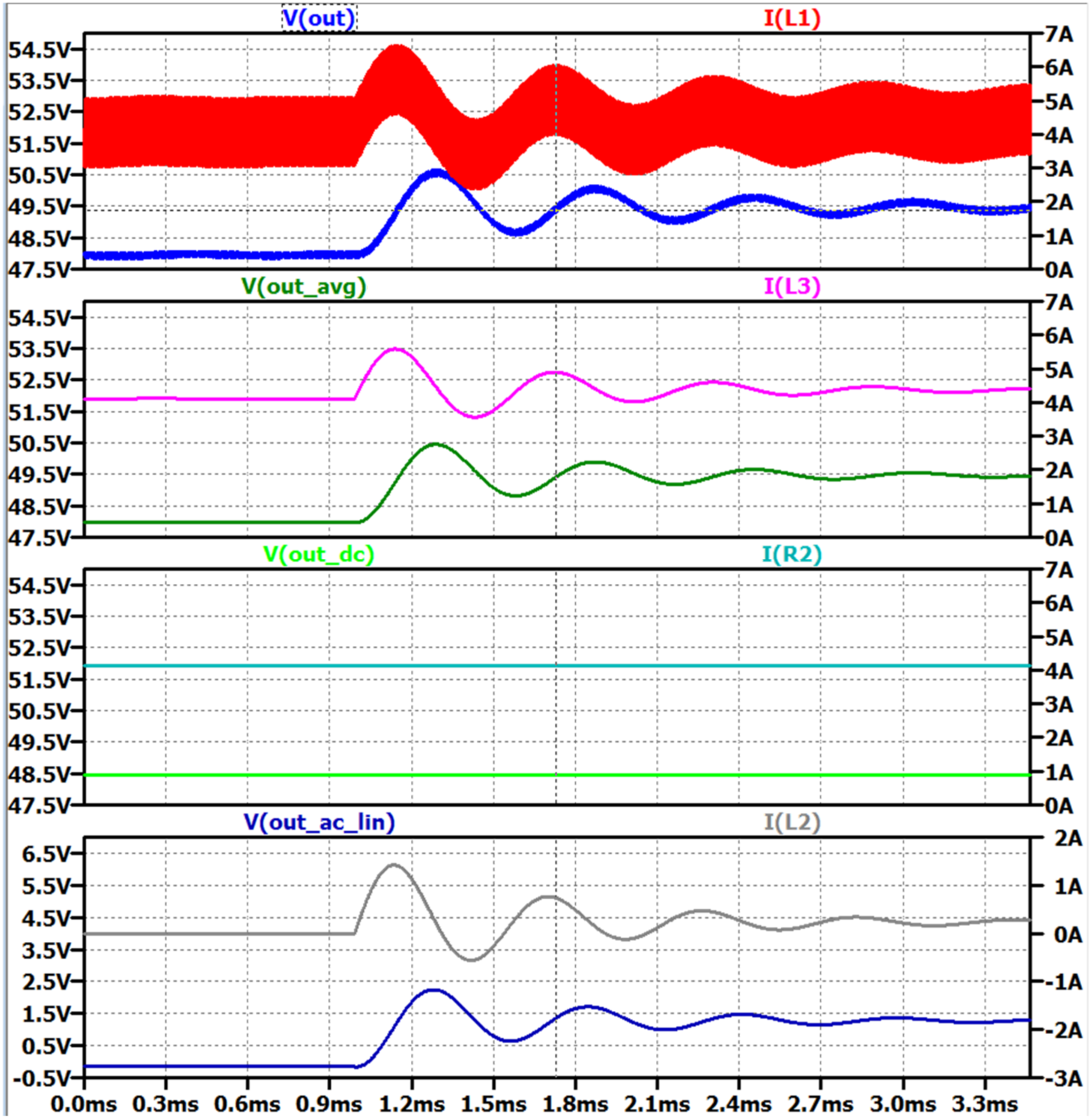
.lib switch.lib
.lib myParts.lib
.tran 0 20m 3m

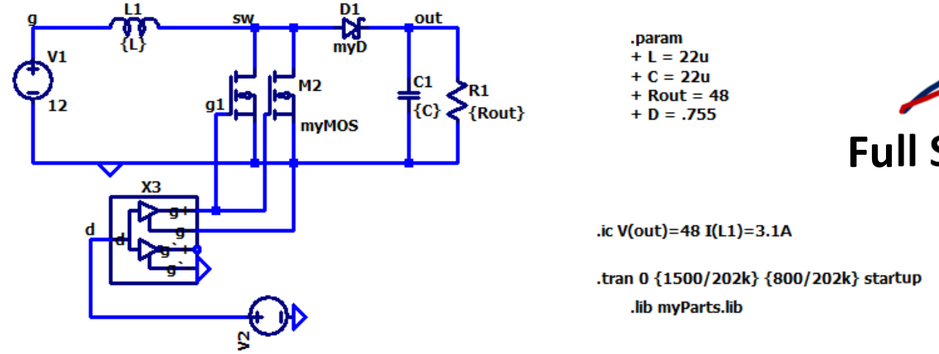
.param Vg = 28 V = 15 R = 3 D = .536
.param Vref = 5 H = 1/3 Vm = 4
.param L = 50u C = 500u

.ic V(out) = 15 I(L1) = 5 V(vc) = {D*Vm}



Model Simulation (L24)

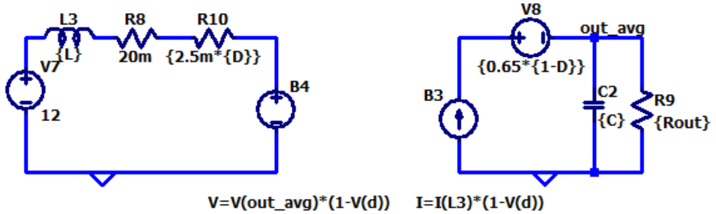




```
.param
+ L = 22u
+ C = 22u
+ Rout = 48
+ D = .755
.ic V(out)=48 I(L1)=3.1A
.tran 0 {1500/202k} {800/202k} startup
.lib myParts.lib
```

only transient sims

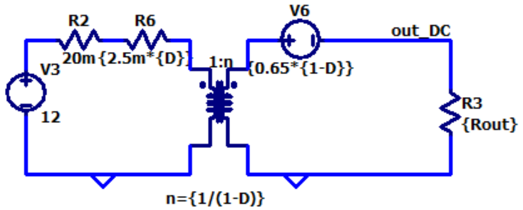
Full Switching Model



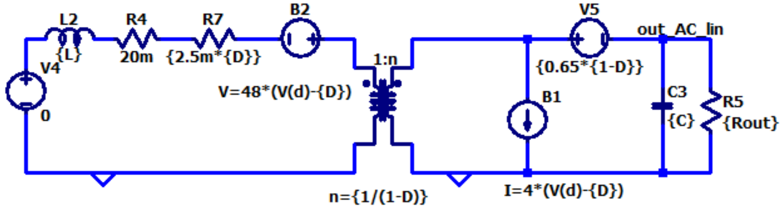
```
.ic V(out_avg)=48 I(L3)=4A
```

ac, transient .op simulations

Averaged, Nonlinear



DC Averaged Model

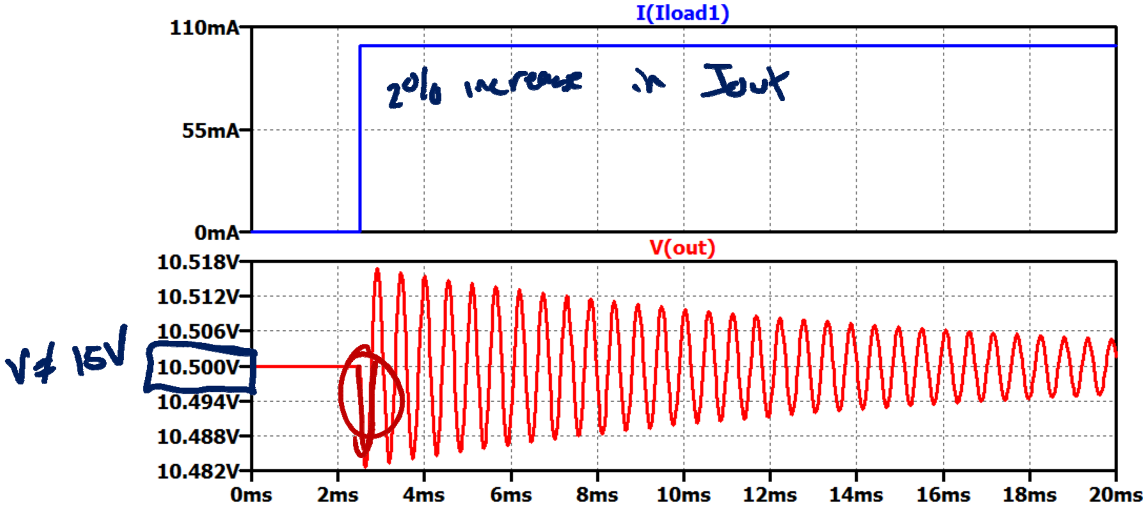


```
.ic V(out_AC_lin)=0 I(L2)=0
```

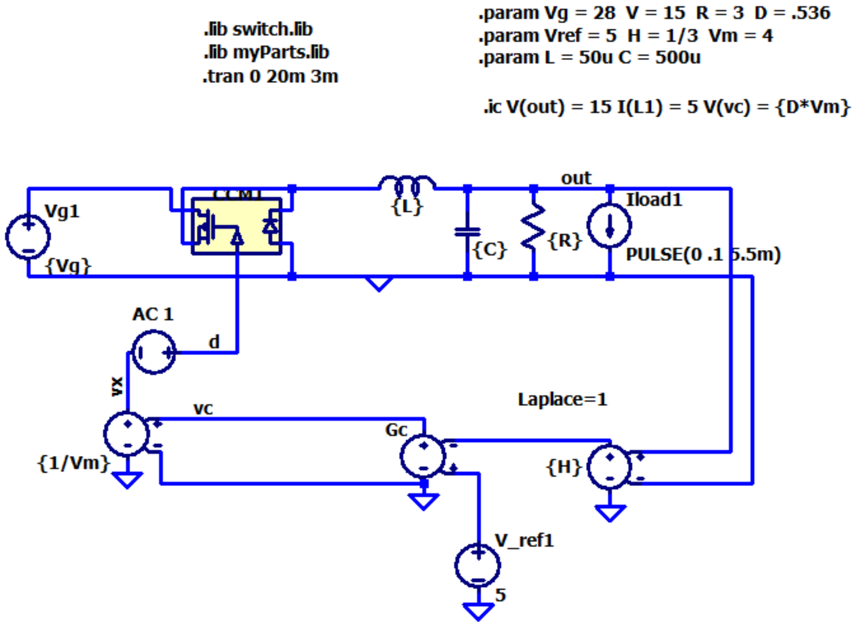
.ac, .tran .op all ok

AC Averaged, Linearized Model

Transient Simulation, Uncompensated



$$V_{ref}\frac{1}{H}\frac{\|T_0\|}{1+\|T_0\|} = (15V)\frac{2.33}{1+2.33} = 10.5V$$

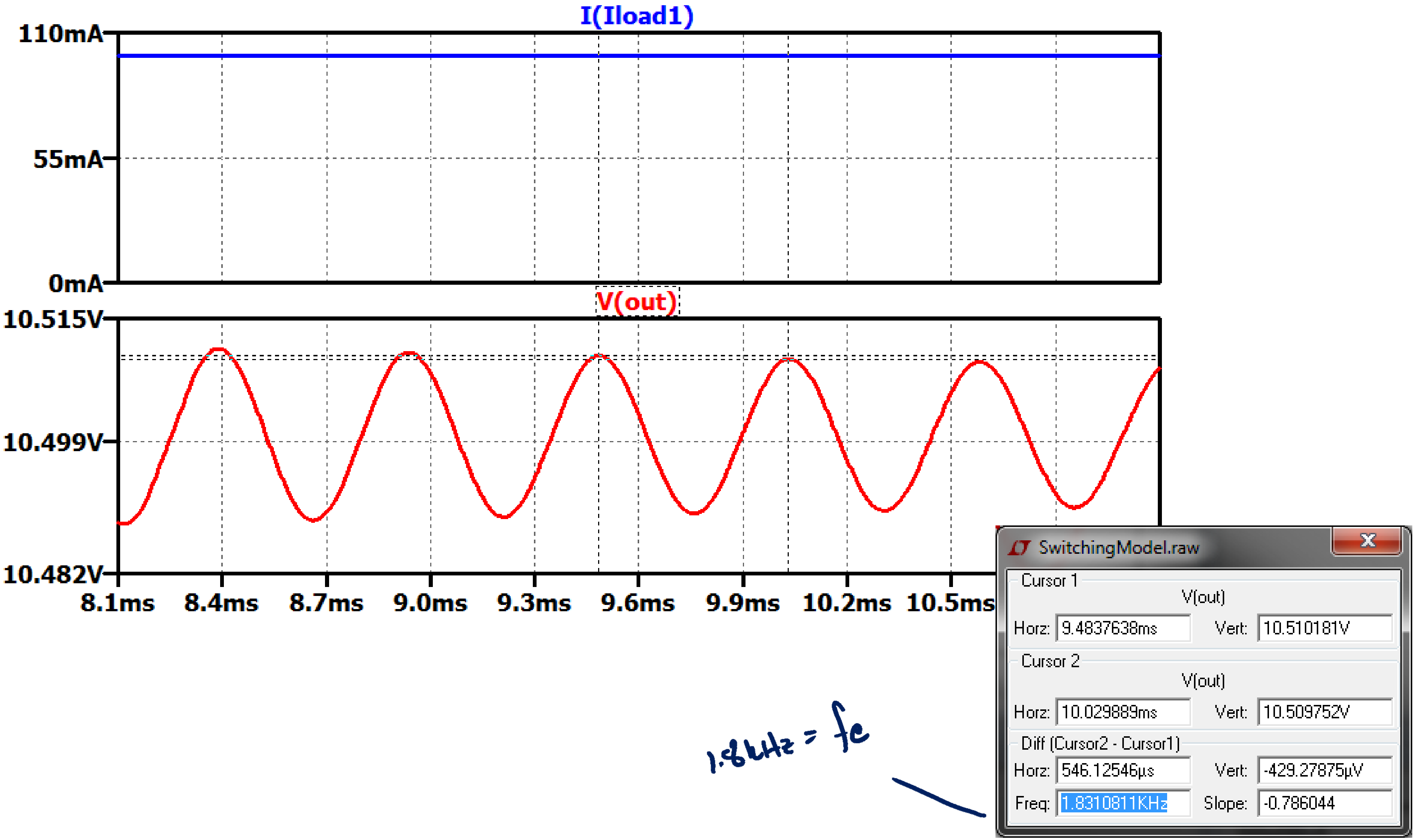


```
.lib switch.lib
.lib myParts.lib
.tran 0 20m 3m
```

```
.param Vg = 28  V = 15  R = 3  D = .536
.param Vref = 5  H = 1/3  Vm = 4
.param L = 50u C = 500u

.ic V(out) = 15 I(L1) = 5 V(vc) = {D*Vm}
```

Ringing Frequency



Cursor 1

V(out)

Horz: 9.4837638ms Vert: 10.510181V

Cursor 2

V(out)

Horz: 10.029889ms Vert: 10.509752V

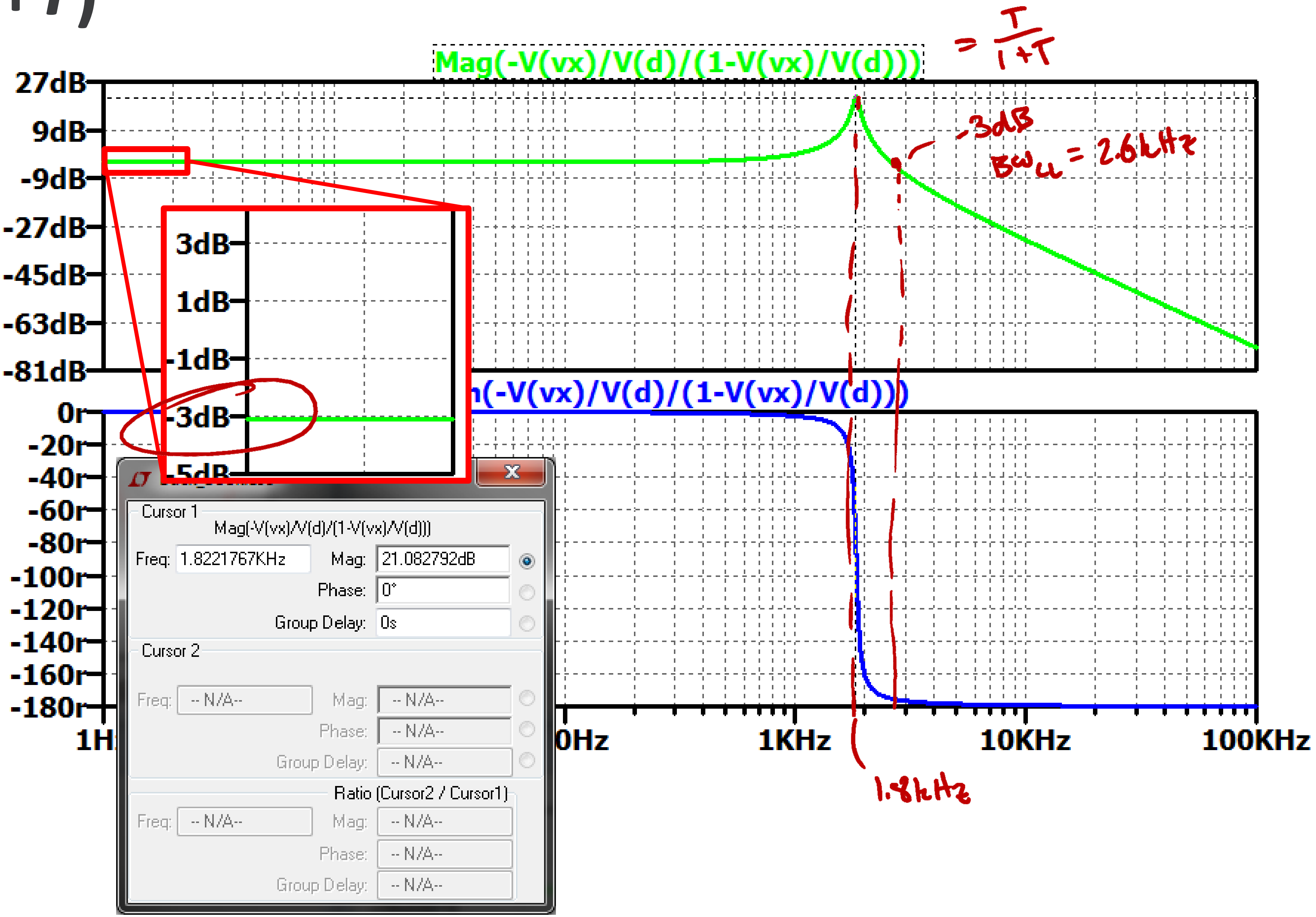
Diff (Cursor2 - Cursor1)

Horz: 546.12546µs Vert: -429.27875µV

Freq: 1.8310811KHz Slope: -0.786044

1.8kHz = f_c

T/(1+T)



Cursor 1

Mag(-V(vx)/V(d)/(1-V(vx)/V(d)))

Freq: 1.8221767KHz Mag: 21.082792dB ●

Phase: 0° ○

Group Delay: 0s ○

Cursor 2

Freq: -- N/A-- Mag: -- N/A-- ○

Phase: -- N/A-- ○

Group Delay: -- N/A-- ○

Ratio (Cursor2 / Cursor1)

Freq: -- N/A-- Mag: -- N/A--

Phase: -- N/A--

Group Delay: -- N/A--

Summary: Uncompensated Behavior

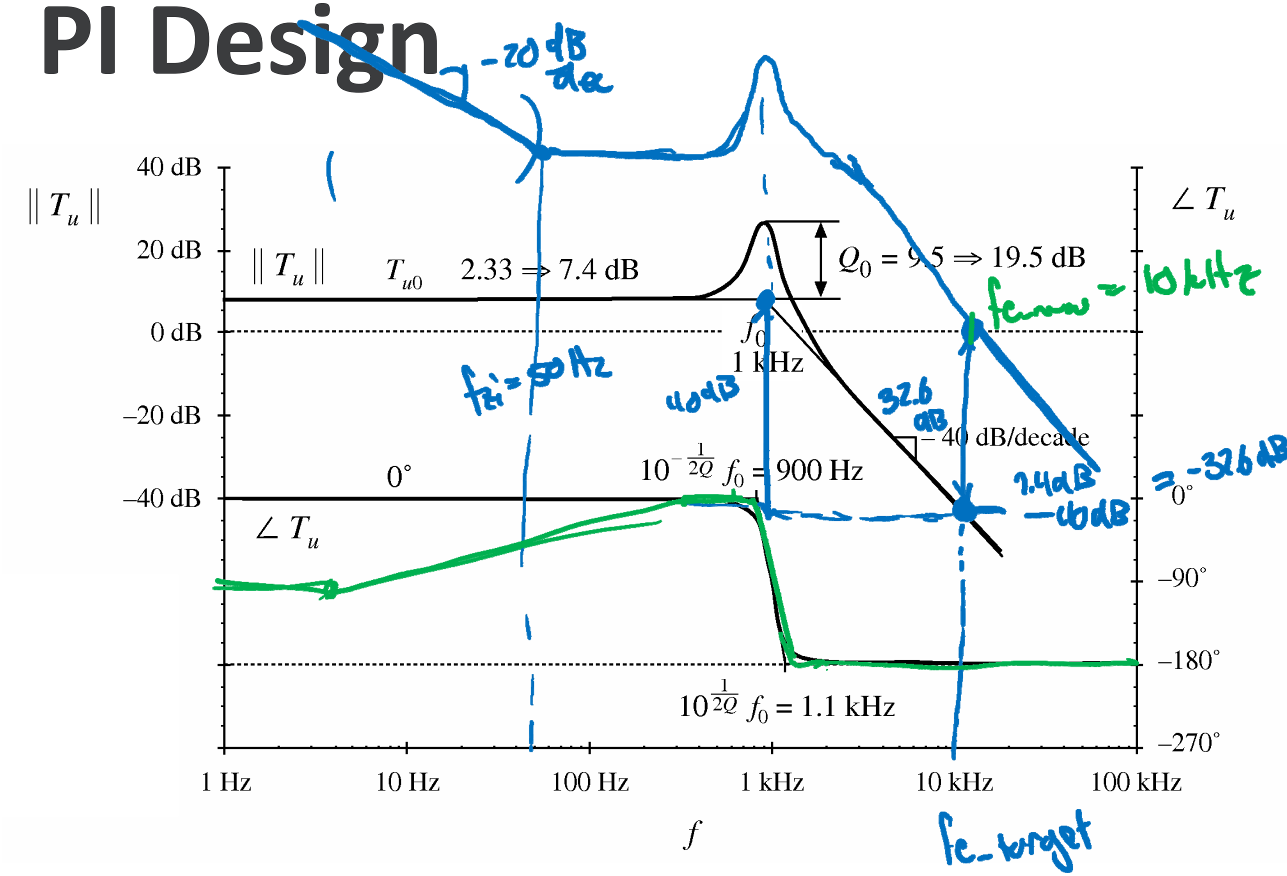
- Significant steady-state error
  - Need to increase low-frequency gain
- Barely stable; significant ringing
  - Need to increase ϕ_m
- Speed: ~ok
  - f_c = 1.8 kHz
  - $(BW)_{CL}$ = 2.6 kHz
  - OK for $f_s \approx$ 10 kHz or above

Compensator Design

- As an example, try to
  - Increase f_c to 10 kHz $= \frac{f_s}{10}$
  - Increase ϕ_m to 76° (Q_{CL}=0.5) → No ringing
  - Increase $\|T_0\|$ to ∞ → zero steady-state error

- Note: Book Chooses f_c = 5 kHz and ϕ_m =52° (Q=1)

PI Design



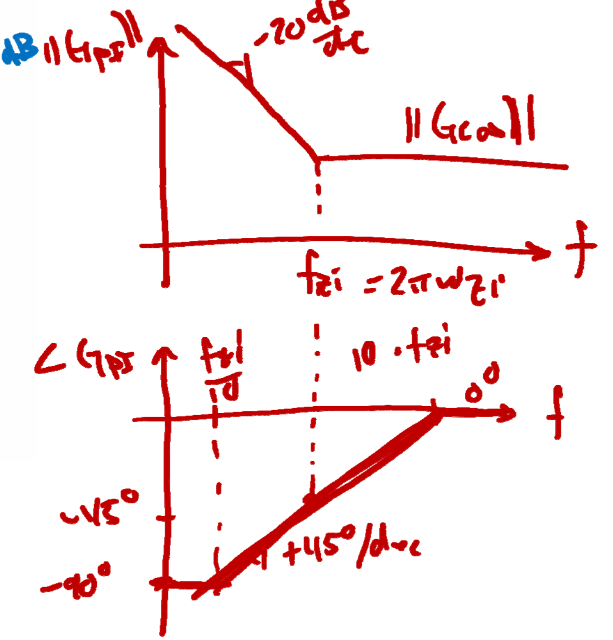
Design PI to give

(1) $f_c = 10$ kHz → use $G_{c\infty}$ to move f_c

(2) $\|T_0\| \to \infty$ → Inherent

(3) Not significantly hurt φ_m → $f_{zi} \ll \frac{f_c}{10}$

$$G_{PI}(s) = G_{c\infty}\left(1 + \frac{\omega_{zi}}{s}\right)$$

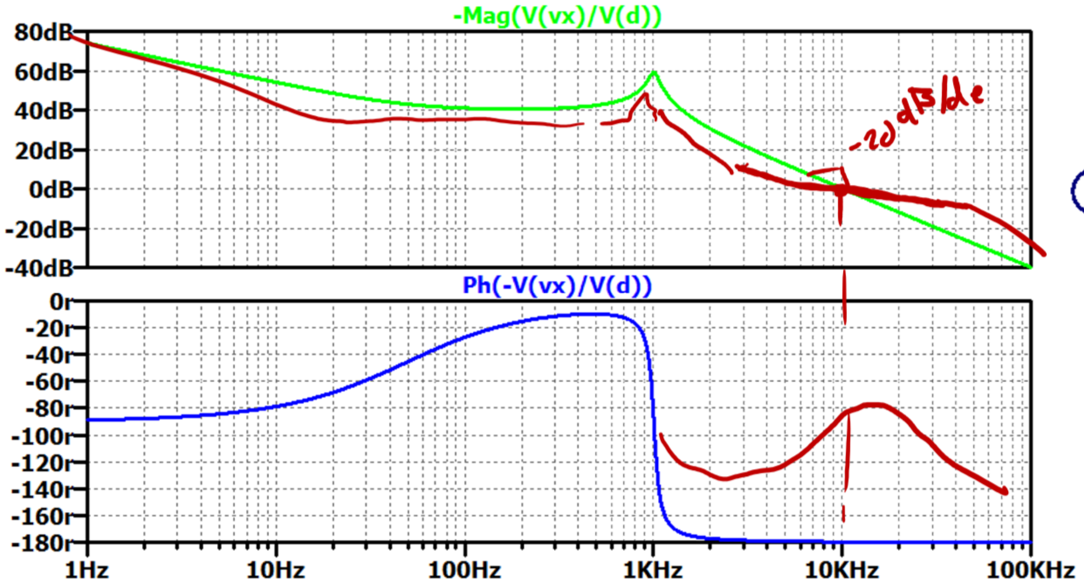


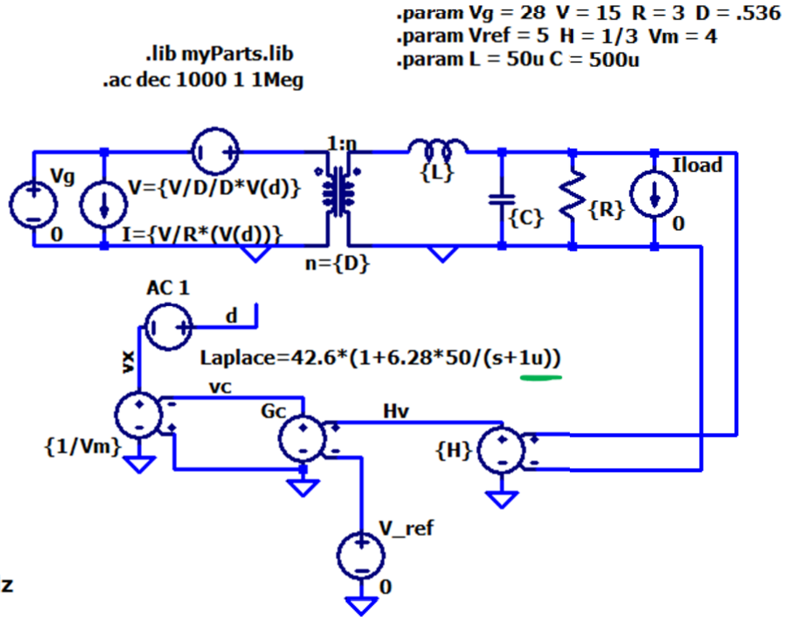
set $G_{c\infty}$ to 32.6 dB = 42.6 to move f_c to 10kHz

& set f_{zi} = 50 Hz

$$G_{PI} = 42.6\left(1 + \frac{2\pi 50}{s}\right)$$

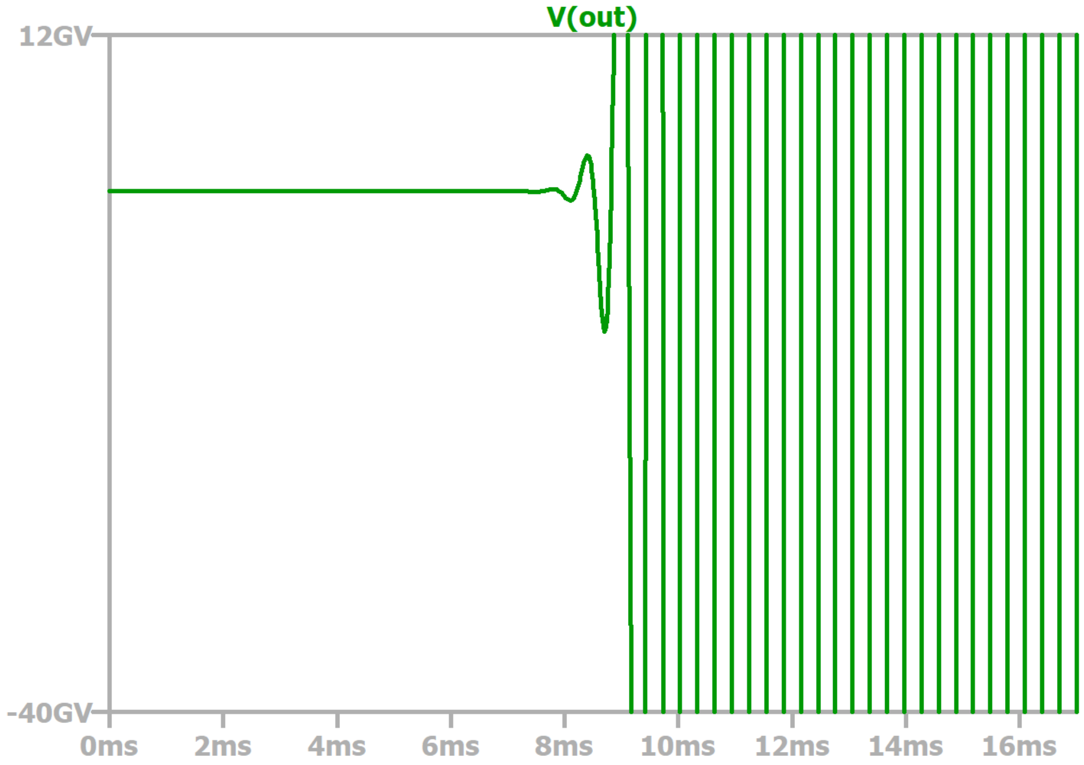
PI Simulation





```
.param Vg = 28  V = 15  R = 3  D = .536
.param Vref = 5  H = 1/3  Vm = 4
.param L = 50u C = 500u
.lib myParts.lib
.ac dec 1000 1 1Meg
```

PI Transient Simulation



PD Design

$$f_z = f_c \sqrt{\frac{1-\sin(\theta)}{1+\sin(\theta)}}$$

$$f_p = f_c \sqrt{\frac{1+\sin(\theta)}{1-\sin(\theta)}}$$

$$G_{c0} = \sqrt{\frac{f_z}{f_p}}$$

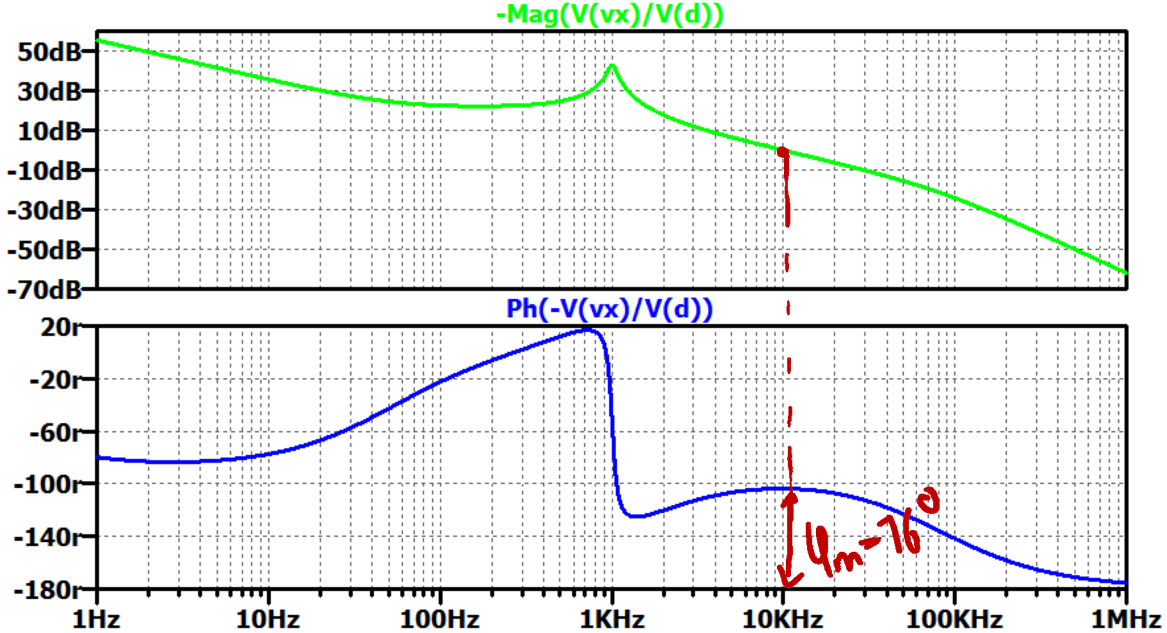
Design: wanted $\varphi_m = 76°$

currently have $\varphi_m = 0°$

↳ set $\theta = 76°$

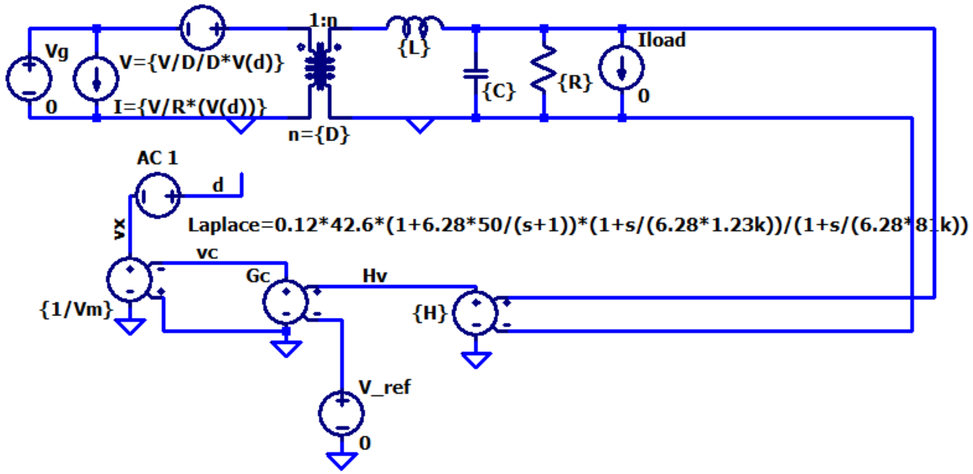
$$\boxed{G_{PD} = G_{c0} \frac{1+\frac{s}{\omega_z}}{1+\frac{s}{\omega_p}}}$$

PID Simulation

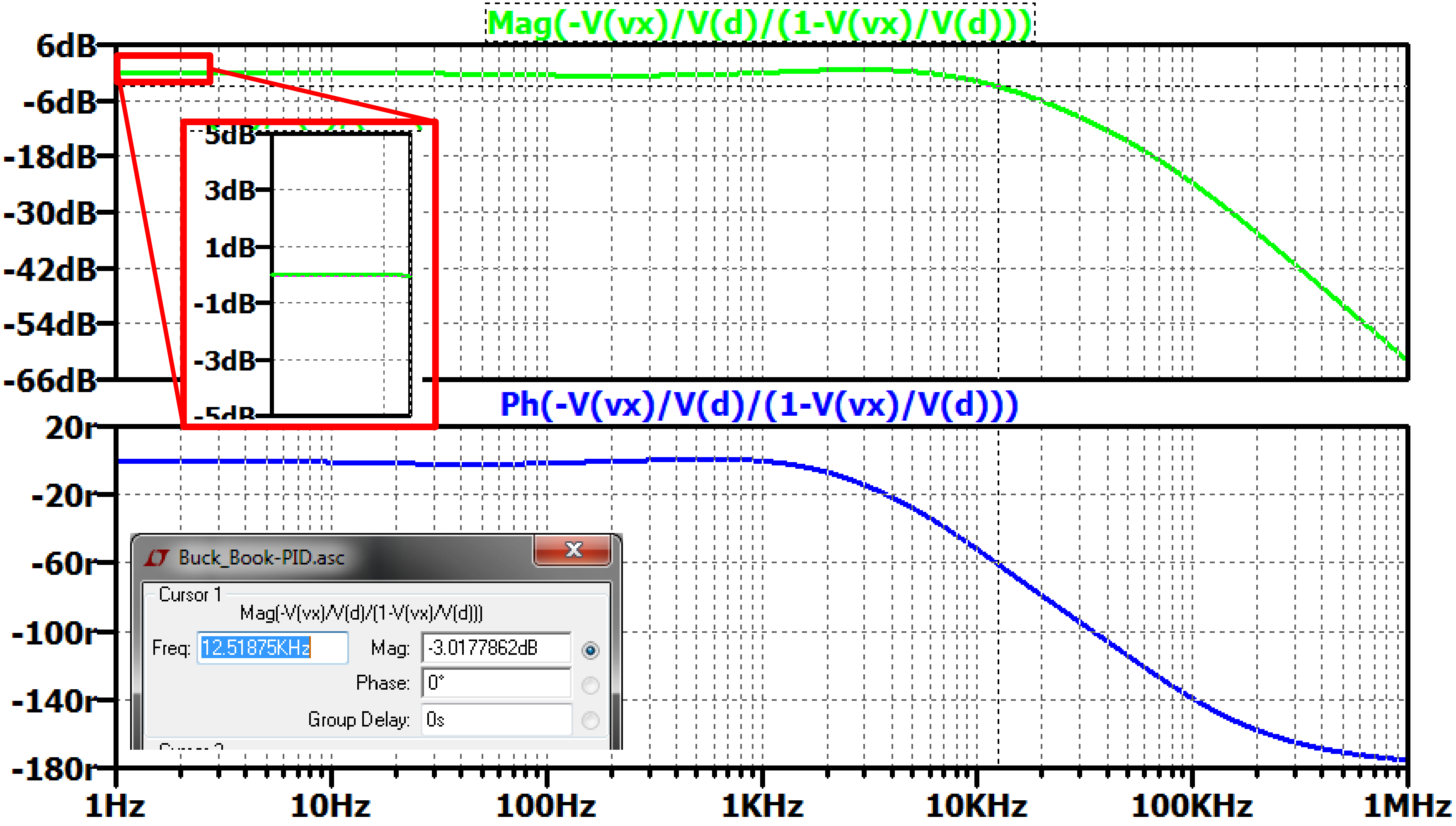


φm-76°

```
.param Vg = 28  V = 15  R = 3  D = .536
.param Vref = 5  H = 1/3  Vm = 4
.param L = 50u C = 500u
.lib myParts.lib
.ac dec 1000 1 1Meg
```



T/(1+*T*)



Cursor 1

Mag(-V(vx)/V(d)/(1-V(vx)/V(d)))

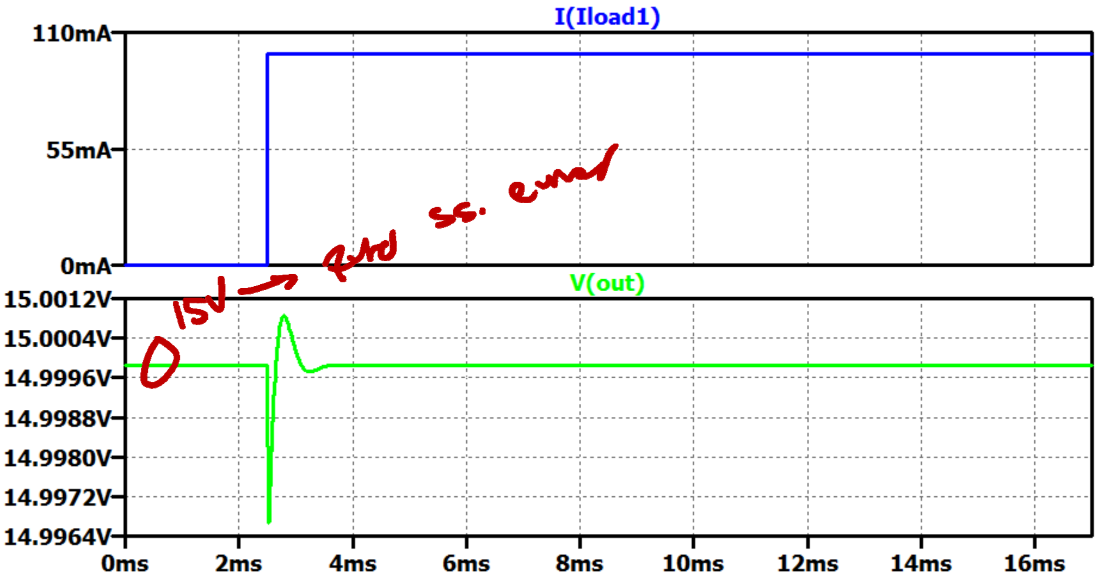
Freq: 12.51875KHz

Mag: -3.0177862dB ●

Phase: 0° ○

Group Delay: 0s ○

Transient Simulation

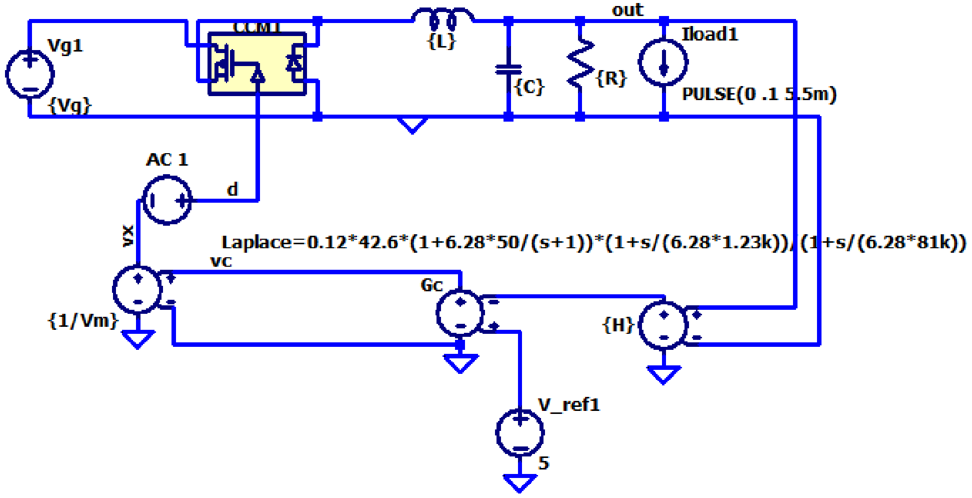


0 15V → Rtd s.s. error

```
.lib switch.lib
.lib myParts.lib
.tran 0 20m 3m
```

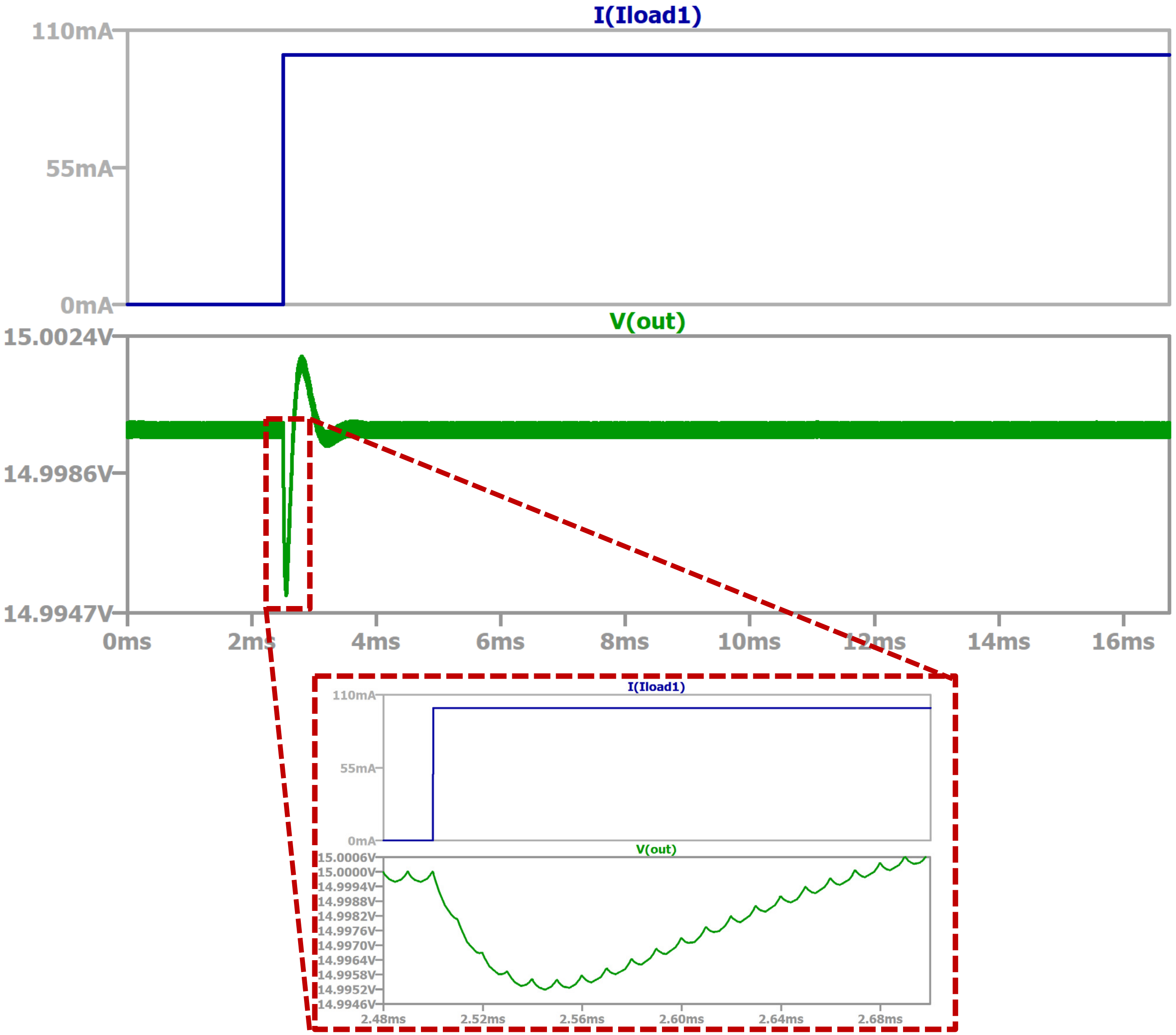
```
.param Vg = 28  V = 15  R = 3  D = .536
.param Vref = 5  H = 1/3  Vm = 4
.param L = 50u C = 500u

.ic V(out) = 15 I(L1) = 5 V(vc) = {D*Vm}
```



Laplace=0.12*42.6*(1+6.28*50/(s+1))*(1+s/(6.28*1.23k))/(1+s/(6.28*81k))

Switching Simulation



```
.step param Vg 16 35 2

.param Vg = 28  V = 15  R = 3  D = .536
.param Vref = 5  H = 1/3  Vm = 4
.param L = 50u C = 500u
```

```
.lib switch.lib
.lib myParts.lib
.tran 0 20m 3m
```

```
.ic V(out) = 15 I(L1) = 5 V(vc) = {D*Vm}
```