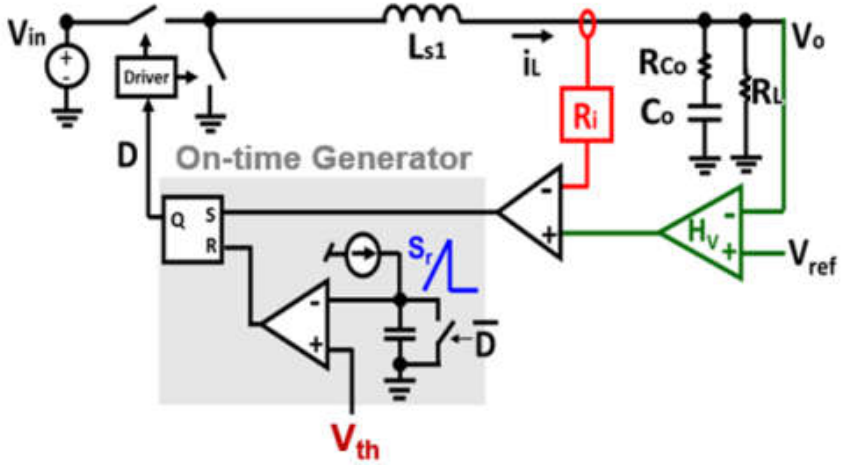
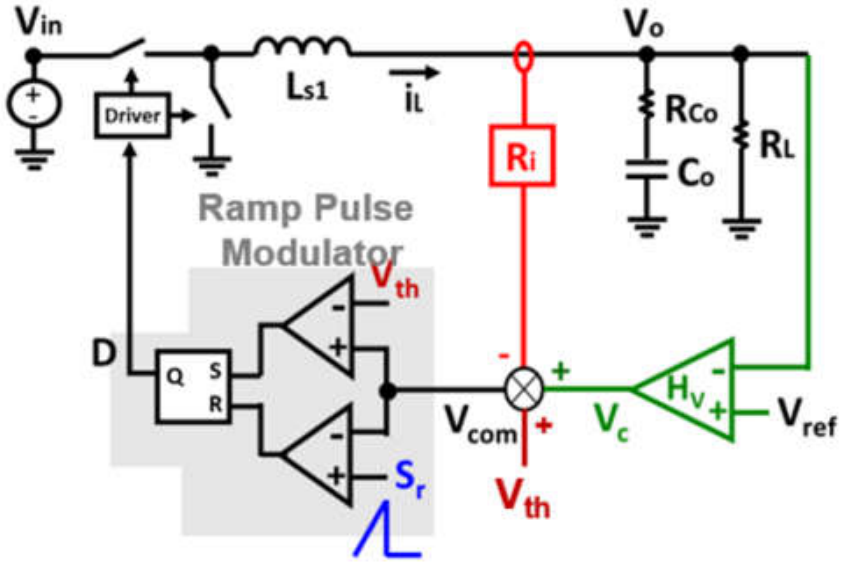
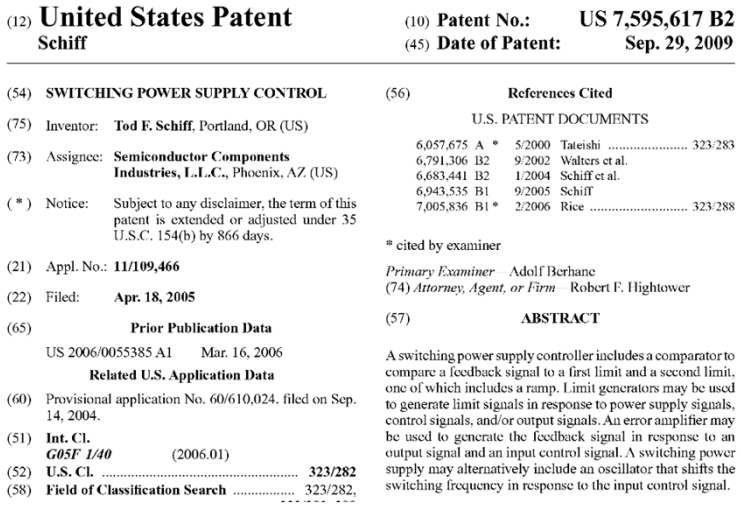


The classical constant on-time (COT) structure



The improved version in a ramp-pulsed-modulated (RPM) structure

V. Li, P. Liu, Q. Li, F. Lee, *Improved Current-Mode Control with Single-Cycle Load transient*, Applied Power Electronics Conference 2016, Long Beach (CA)



(12) **United States Patent**
Schiff

(10) **Patent No.: US 7,595,617 B2**
(45) **Date of Patent: Sep. 29, 2009**

(54) **SWITCHING POWER SUPPLY CONTROL**

(75) Inventor: **Tod F. Schiff**, Portland, OR (US)

(73) Assignee: **Semiconductor Components Industries, L.L.C.**, Phoenix, AZ (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 866 days.

(21) Appl. No.: **11/109,466**

(22) Filed: **Apr. 18, 2005**

(65) **Prior Publication Data**

US 2006/0055385 A1 Mar. 16, 2006

Related U.S. Application Data

(60) Provisional application No. 60/610,024, filed on Sep. 14, 2004.

(51) **Int. Cl.**
G05F 1/40 (2006.01)

(52) **U.S. Cl.** **323/282**

(58) **Field of Classification Search** 323/282,

(56) **References Cited**

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7,005,836	B1 *	2/2006	Rice	323/288

* cited by examiner

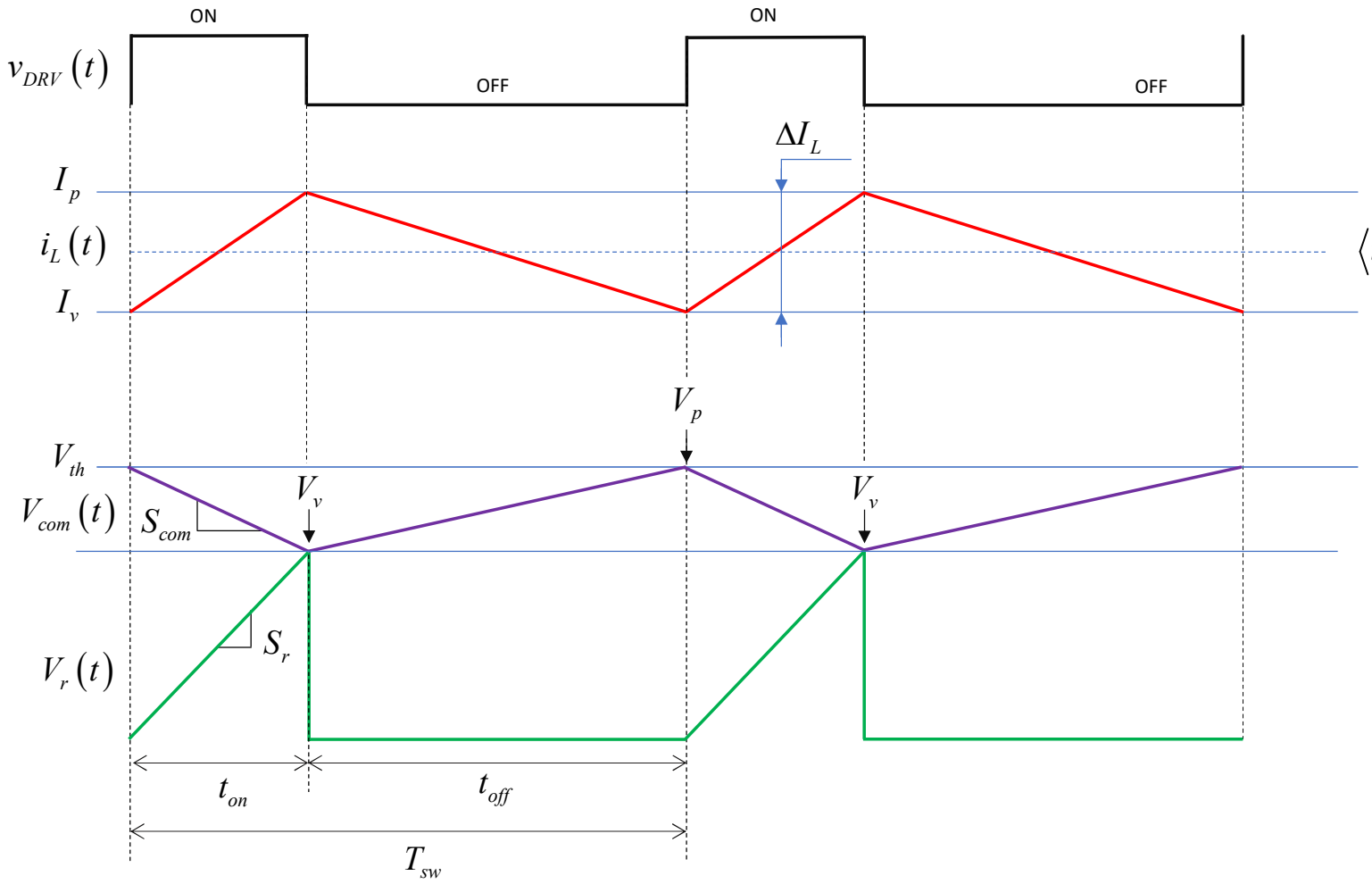
Primary Examiner — Adolf Berhane
(74) *Attorney, Agent, or Firm* — Robert F. Hightower

(57) **ABSTRACT**

A switching power supply controller includes a comparator to compare a feedback signal to a first limit and a second limit, one of which includes a ramp. Limit generators may be used to generate limit signals in response to power supply signals, control signals, and/or output signals. An error amplifier may be used to generate the feedback signal in response to an output signal and an input control signal. A switching power supply may alternatively include an oscillator that shifts the switching frequency in response to the input control signal.

Original RPM patent dates from 2009

An average model for the ramp-pulse-modulated (RPM) converter
Christophe Basso – November 2020



I have considered steady-state conditions only to derive the small-signal model. Literature points to a dynamic up-slope change during transient but it complicates the model. As you will see, the average model incorporates a dynamically-moving t_{on} generator and final results are in excellent agreement with SIMPLIS.

Steady-state CCM operation

An average model for the ramp-pulse-modulated (RPM) converter
Christophe Basso – November 2020

$$S_n = \frac{V_{in} - V_{out}}{L} = \frac{V_{ac}}{L} \qquad S_r = \frac{I_{chg}}{C_t} \quad \text{Charging slope} \qquad S_{com} = S_n$$

$$t_{on} S_r = V_{th} - t_{on} S_{com} \Rightarrow t_{on} = \frac{V_{th}}{S_n R_i + S_r}$$

From PWM switch: $\Rightarrow t_{off} = \frac{V_{ac}}{V_{cp}} t_{on}$

$$F_{sw} = \frac{1}{t_{on} + t_{off}} \Rightarrow F_{sw} = \frac{V_{cp}}{V_{ac} + V_{cp}} \frac{S_r + R_i S_n}{V_{th}}$$

Inductor ripple current:

$$\Delta I_L = \frac{V_{in} - V_{out}}{L} t_{on} = \frac{V_{ac}}{L} \frac{V_{th}}{\frac{V_{ac}}{L} R_i + S_r} = \frac{V_{ac} V_{th}}{L S_r + R_i V_{ac}}$$

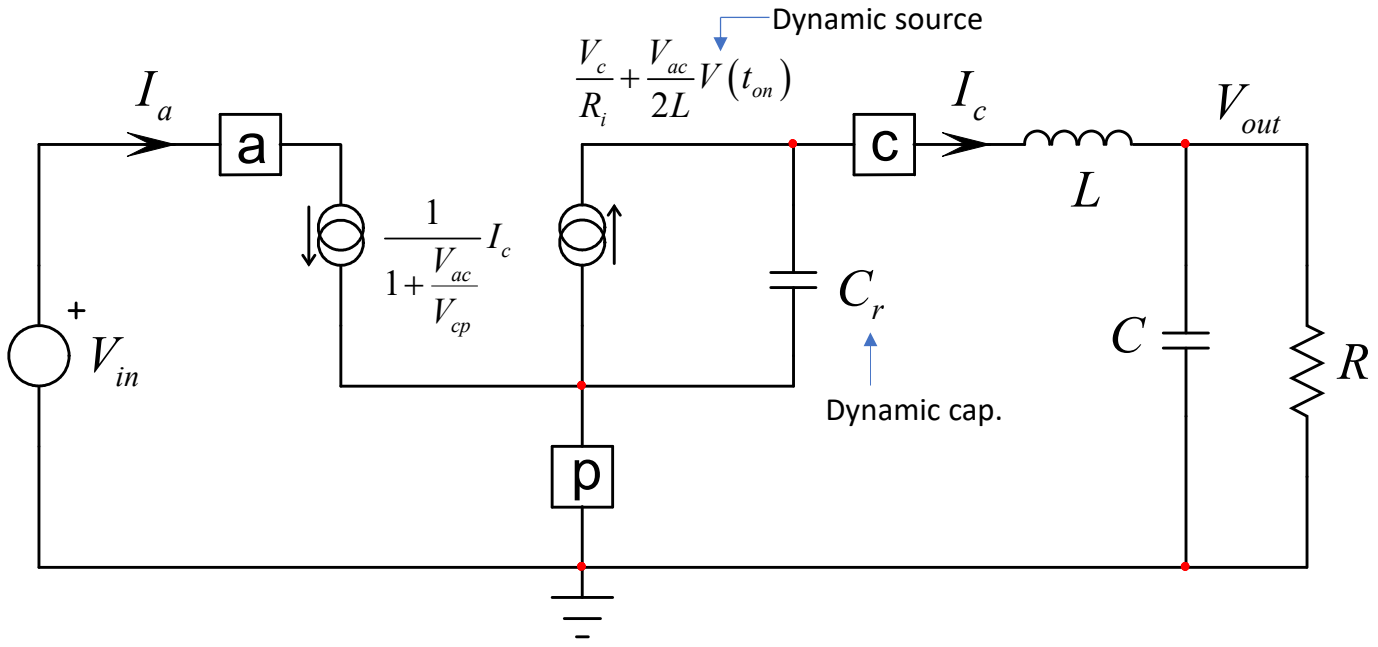
Valley current: $I_v = \frac{V_c}{R_i}$

Peak current: $I_c = I_v + \Delta I_L$

$$I_c = I_v + \frac{\Delta I_L}{2} = \frac{V_c}{R_i} + \frac{V_{ac}}{2L} t_{on}$$

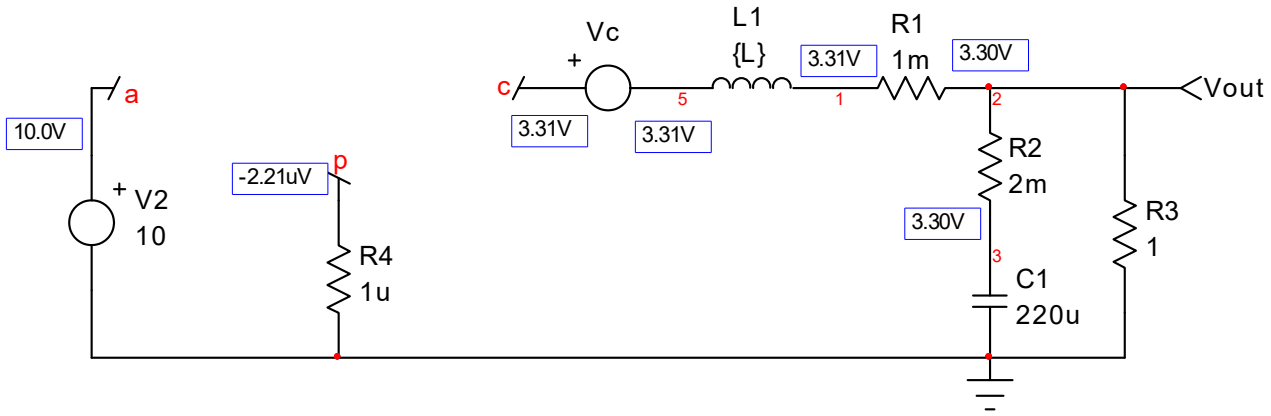
Dynamic source

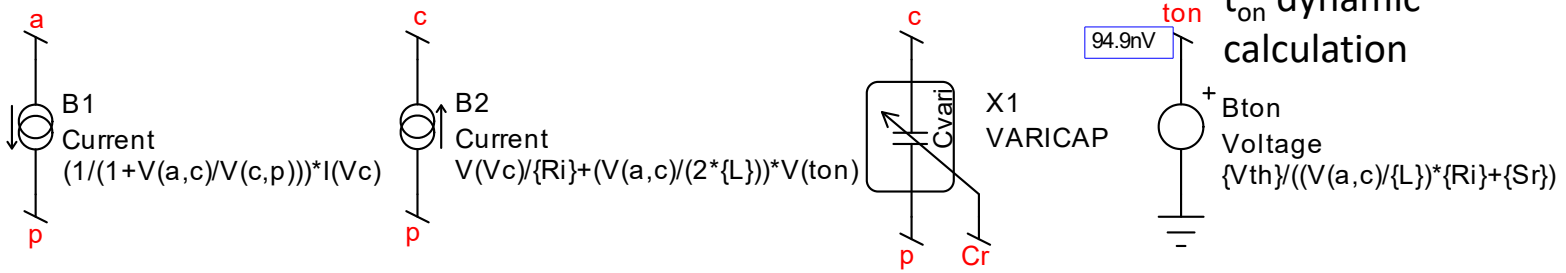
Final model with PWM switch:



Parameters

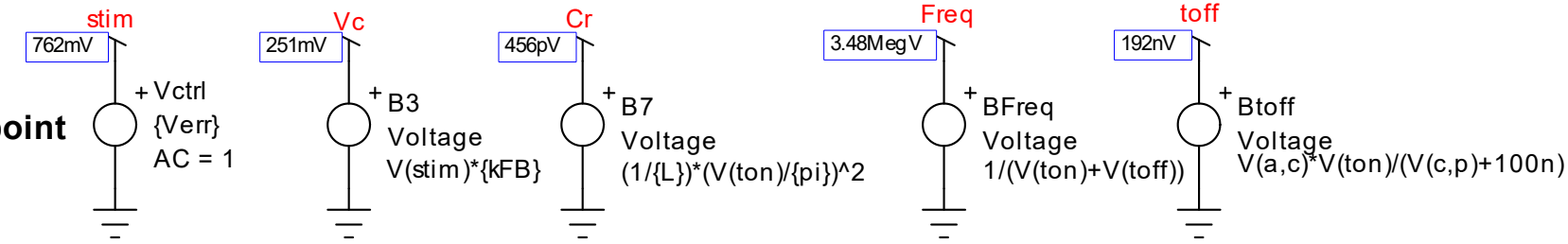
Ri=80m
L=2u
pi=3.14159
Ct=2p
Ichg=10u
Sr=Ichg/Ct
Vth=0.5
Verr=762m
kFB=0.33



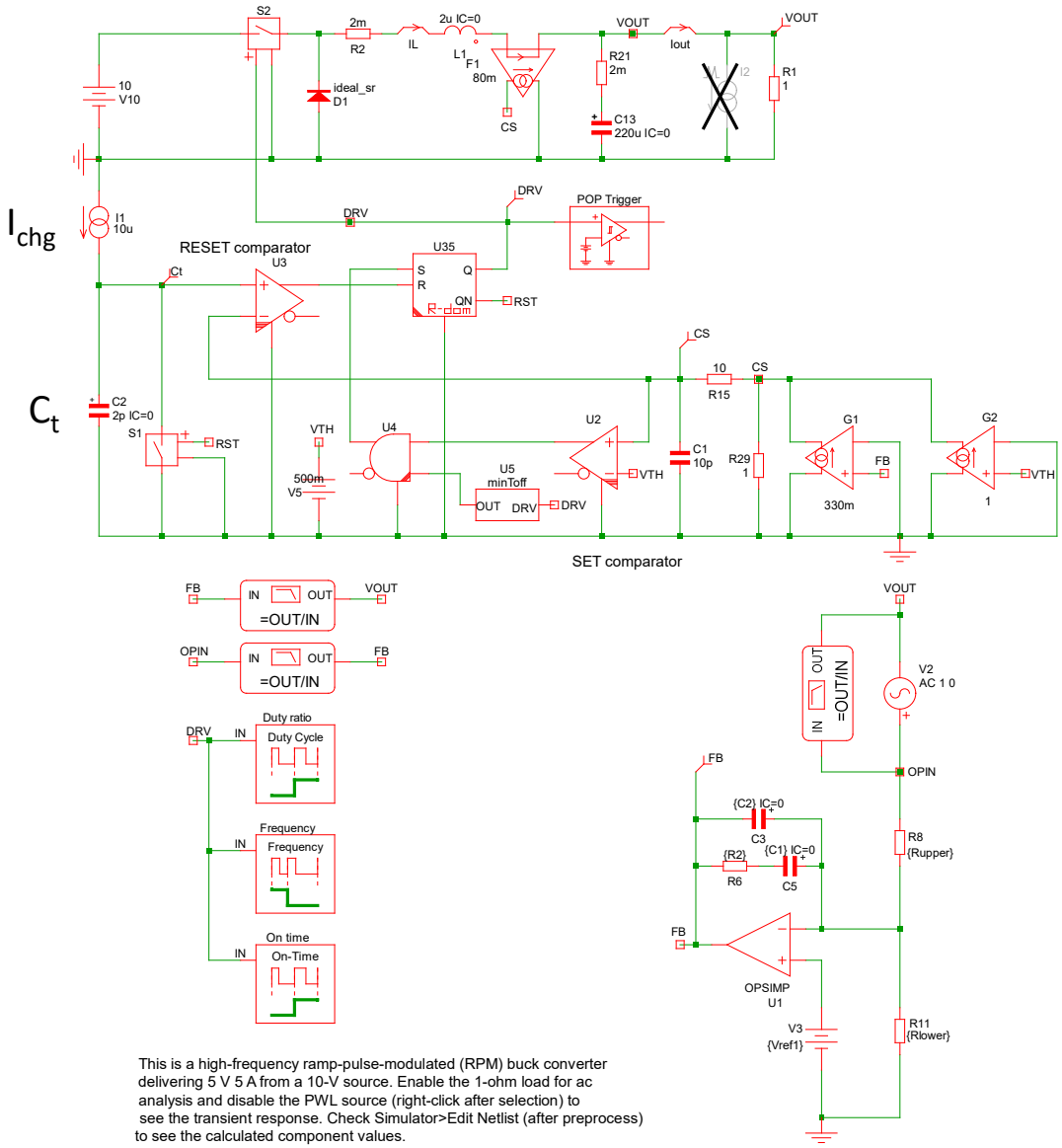


t_{on} dynamic calculation

Control Voltage
Valley Current Setpoint



456-pF capacitor

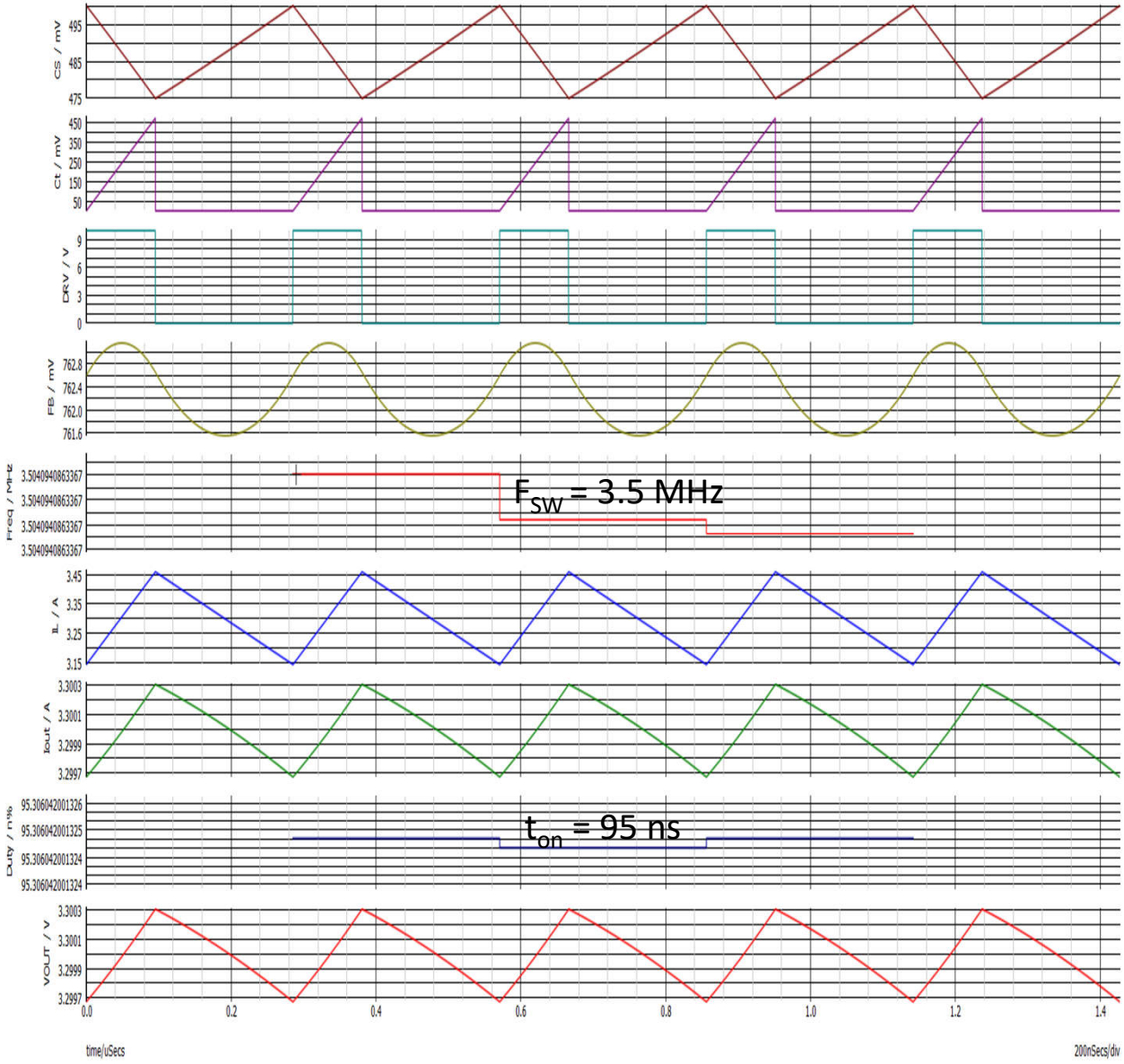


This is a high-frequency ramp-pulse-modulated (RPM) buck converter delivering 5 V 5 A from a 10-V source. Enable the 1-ohm load for ac analysis and disable the PWL source (right-click after selection) to see the transient response. Check Simulator>Edit Netlist (after preprocess) to see the calculated component values.

- Christophe Basso - Transfer Functions of Switching Converters -

```
*
.VAR Vin=10
.VAR Vout=3.3
*
.VAR Gfc=-30.5 * magnitude at crossover *
.VAR PS=-80 * phase lag at crossover *
*
* Enter Design Goals Information Here *
*
.VAR fc=100k * targetted crossover *
.VAR PM=70 * choose phase margin at crossover *
*
* Enter the Values for Vout and Bridge Bias Current *
*
.VAR Ibias=1m
.VAR Vref1=2.5
.VAR Rlower={Vref1/Ibias}
.VAR Rupper={(Vout-Vref1)/Ibias}
*
* Do not edit the below lines *
.VAR boost=PM-PS-90
.VAR G=10^(-Gfc/20)
.VAR fp=(tan(boost*pi/180)+sqrt((tan(boost*pi/180))^2+1))*fc
.VAR fz=fc^2/fp
.VAR a=sqrt((fc^2/fp^2)+1)
.VAR b=sqrt((fz^2/fc^2)+1)
.VAR R2=((a/b)*G*Rupper*fp)/(fp-fz)
.VAR C1=1/(2*pi*R2*fz)
.VAR C2=C1/(C1*R2*2*pi*fp-1)
*
*
{ '*' }
{ '*' } Rupper = {Rupper}
{ '*' } Rlower = {Rlower}
{ '*' } R2 = {R2}
{ '*' } C2 = {C2}
{ '*' } C1 = {C1}
{ '*' } Boost = {boost}
{ '*' } Fz = {Fz}
{ '*' } Fp = {Fp}
{ '*' }
```

SIMPLIS model with automatic compensation macro for a 100-kHz crossover.



Ramp Pulse Modulation (RPM) operating point calculations:

$I_{chg} := 10\mu A$ $C_t := 2pF$ $V_{in} := 10V$ $V_{out} := 3.3V$ $L_1 := 2\mu H$ $R_i := 0.08\Omega$

$V_{th} := 0.5V$ $V_{ac} := V_{in} - V_{out} = 6.7V$ $V_{cp} := V_{out}$ $V_{err} := 762mV$ $k_{FB} := 0.330$

$S_r := \frac{I_{chg}}{C_t} = 5\frac{V}{\mu s}$ $S_n := \frac{V_{in} - V_{out}}{L_1} = 3.35\frac{A}{\mu s}$ $S_n = \frac{V_{ac}}{L}$

$t_{on} := \frac{V_{th}}{S_n \cdot R_i + S_r} = 94.913ns$ $t_{off} := \frac{V_{ac}}{V_{cp}} \cdot t_{on} = 192.702ns$ $S_{com} := S_n \cdot R_i$

$F_{sw} := \frac{1}{t_{on} + t_{off}} = 3.477MHz$ $\frac{V_{cp} \cdot (S_r + R_i \cdot S_n)}{V_{th} \cdot (V_{ac} + V_{cp})} = 3.477MHz$

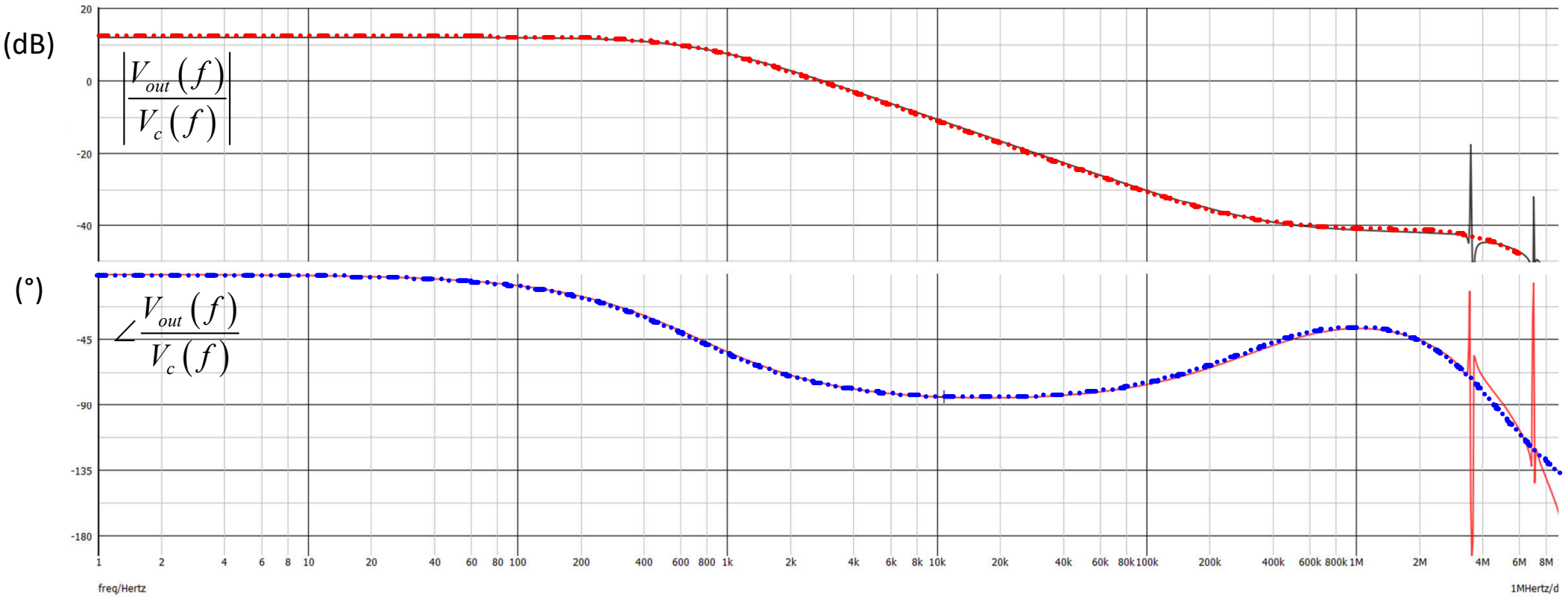
$V_v = V_{th} - S_{com} \cdot t_{on}$ $V_{th} - S_{com} \cdot t_{on} = 0.475V$

$V_v = S_r \cdot t_{on}$

$\Delta I_L := \frac{V_{ac}}{L_1} \cdot \frac{V_{th}}{\frac{V_{ac}}{L_1} \cdot R_i + S_r} = 0.318A$ $\frac{V_{ac} \cdot V_{th}}{L_1 \cdot S_r + R_i \cdot V_{ac}} = 0.318A$

$I_v := \frac{V_{err} \cdot k_{FB}}{R_i} = 3.143A$ $I_p := I_v + \Delta I_L = 3.461A$ $\frac{V_{err} \cdot k_{FB} + V_{th} - S_r \cdot t_{on}}{R_i} = 3.461A$

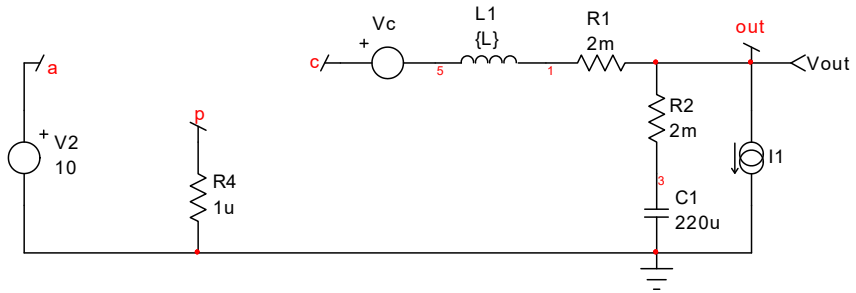
$I_{out} := \frac{I_v + I_p}{2} = 3.302A$

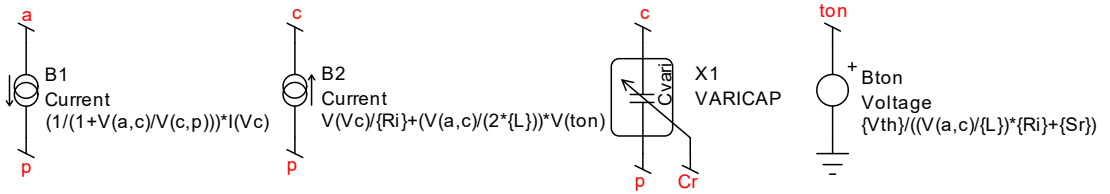


SIMPLIS versus IsSpice with resonating capacitor

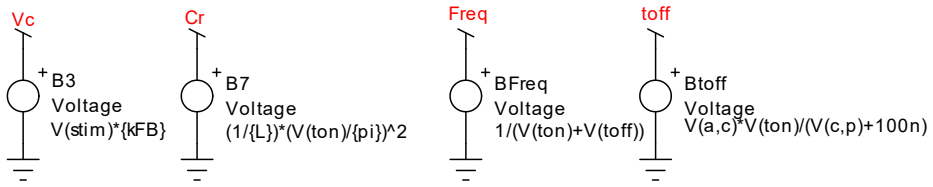
Parameters

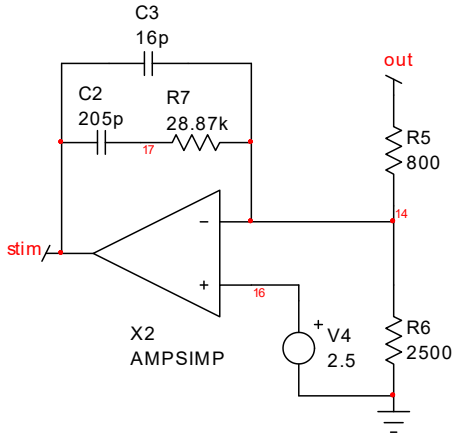
Ri=80m
L=2u
pi=3.14159
Ct=2p
Ichg=10u
Sr=Ichg/Ct
Vth=0.5
Verr=762m
kFB=0.33





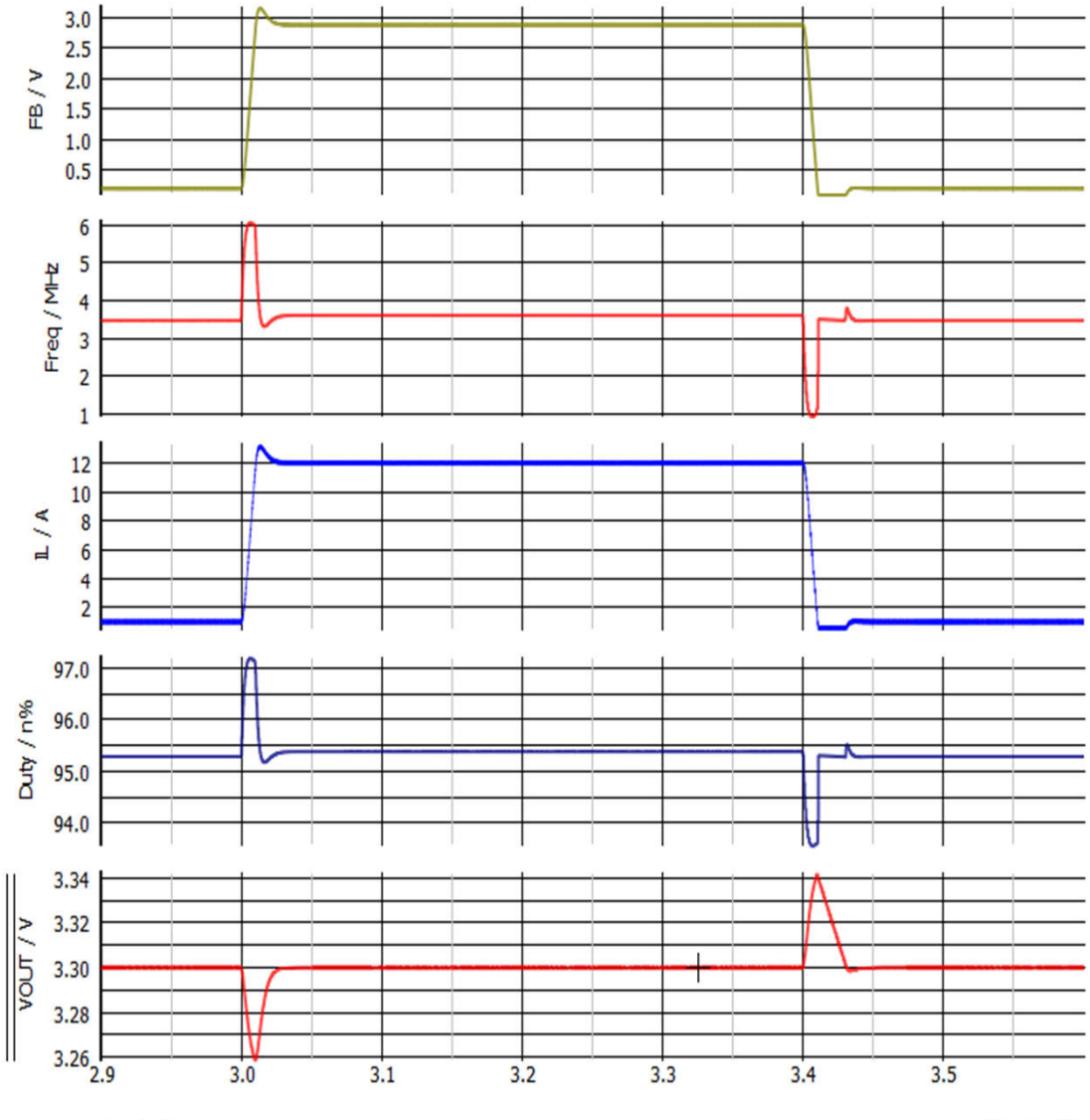
Control Voltage
Valley Current Setpoint



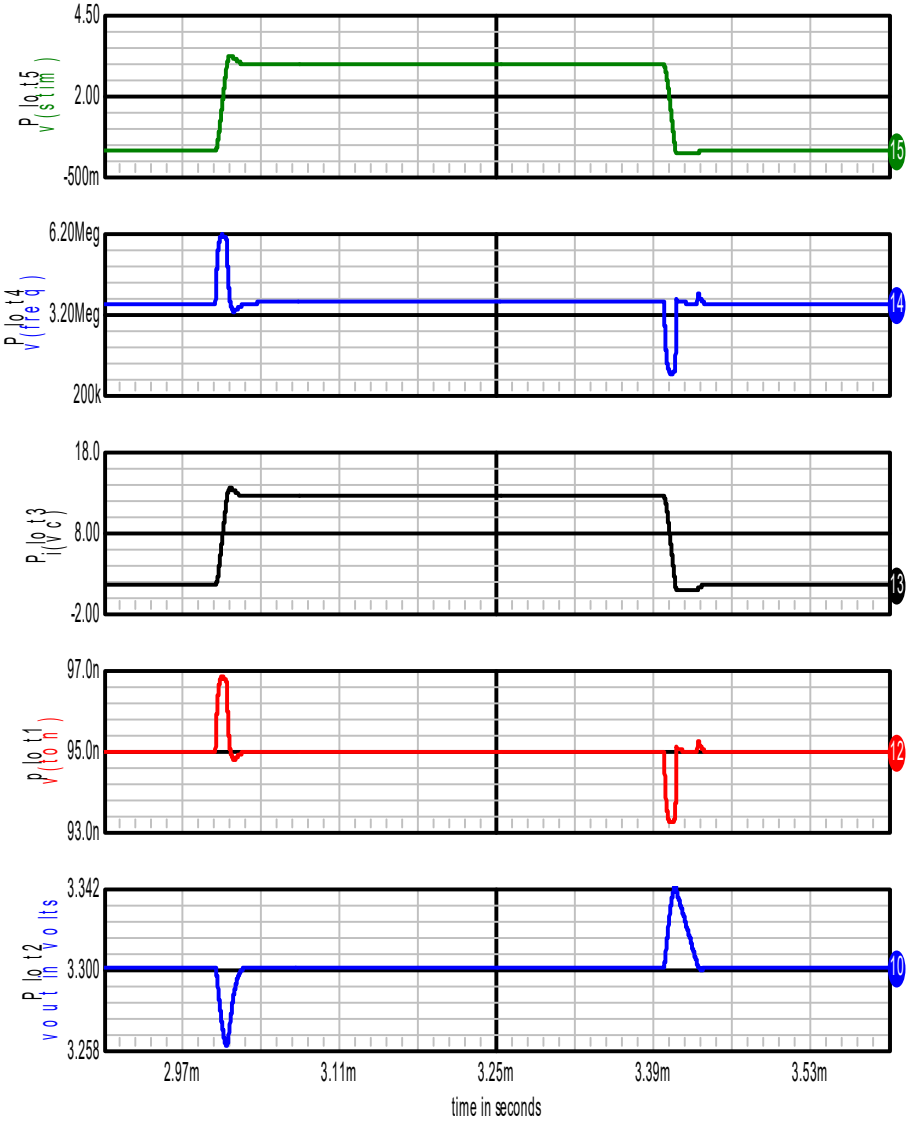


IsSpice model used in transient simulation. Comp. values are those calculated by SIMPLIS

```
*
* Rupper = 800
* Rlower = 2500
* R2 = 28870.0084836725
* C2 = 1.59141188491394e-11
* C1 = 2.05740962712432e-10
* Boost = 60
* Fz = 26794.9192431123
* Fp = 373205.080756888
*
```



SIMPLIS transient, 1 to 12 A in 1 µs



IsSpice avg model transient, 1 to 12 A in 1 µs

Small-signal coefficients:

$$I_a = I_c \cdot \frac{1}{1 + \frac{V_{ac}}{V_{cp}}}$$

$$\frac{d}{dI_c}\left(I_c \cdot \frac{1}{1 + \frac{V_{ac}}{V_{cp}}}\right) \rightarrow \frac{1}{\frac{V_{ac}}{V_{cp}} + 1} \quad k_{ic}$$

$$\frac{d}{dV_{ac}}\left(I_c \cdot \frac{1}{1 + \frac{V_{ac}}{V_{cp}}}\right) \rightarrow -\frac{I_c}{V_{cp} \cdot \left(\frac{V_{ac}}{V_{cp}} + 1\right)^2} \quad k_{ac}$$

$$\frac{d}{dV_{cp}}\left(I_c \cdot \frac{1}{1 + \frac{V_{ac}}{V_{cp}}}\right) \rightarrow \frac{I_c \cdot V_{ac}}{V_{cp}^2 \cdot \left(\frac{V_{ac}}{V_{cp}} + 1\right)^2} \quad k_{cp}$$

$$I_c = \frac{V_{err} \cdot k_{FB}}{R_i} + \frac{V_{ac}}{2 \cdot L_1} \cdot \frac{V_{th}}{\frac{V_{ac}}{L_1} \cdot R_i + S_r}$$

$$\frac{d}{dV_c}\left(\frac{V_c}{R_i} + \frac{V_{ac}}{2 \cdot L_1} \cdot \frac{V_{th}}{\frac{V_{ac}}{L_1} \cdot R_i + S_r}\right) \rightarrow \frac{1}{R_i} \quad k_{vc}$$

$$\frac{d}{dV_{ac}}\left(\frac{V_c}{R_i} + \frac{V_{ac}}{2 \cdot L_1} \cdot \frac{V_{th}}{\frac{V_{ac}}{L_1} \cdot R_i + S_r}\right) \rightarrow \frac{V_{th}}{2 \cdot L_1 \cdot \left(S_r + \frac{R_i \cdot V_{ac}}{L_1}\right)} - \frac{R_i \cdot V_{ac} \cdot V_{th}}{2 \cdot L_1^2 \cdot \left(S_r + \frac{R_i \cdot V_{ac}}{L_1}\right)^2} \quad k_{vac}$$

$I_{chg} := 10\mu A$ $C_t := 2pF$ $V_{in} := 10V$ $V_{out} := 3.3V$ $L_1 := 2\mu H$ $R_i := 0.08\Omega$

$V_{th} := 0.5V$ $V_{ac} := V_{in} - V_{out} = 6.7V$ $V_{cp} := V_{out}$ $V_{err} := 762mV$ $k_{FB} := 0.330$

$S_r := \frac{I_{chg}}{C_t} = 5\frac{V}{\mu s}$ $S_n := \frac{V_{in} - V_{out}}{L_1} = 3.35\frac{A}{\mu s}$ $t_{on} := \frac{V_{th}}{S_n \cdot R_i + S_r} = 94.913ns$

$I_c := \frac{V_{err} \cdot k_{FB}}{R_i} + \frac{V_{ac}}{2 \cdot L_1} \cdot \frac{V_{th}}{\frac{V_{ac}}{L_1} \cdot R_i + S_r} = 3.302A$ $C_r := \frac{1}{L_1} \cdot \left(\frac{t_{on}}{\pi}\right)^2 = 456.372pF$

$k_{ic} := \frac{1}{\frac{V_{ac}}{V_{cp}} + 1} = 0.33$ $k_{ac} := -\frac{I_c}{V_{cp} \cdot \left(\frac{V_{ac}}{V_{cp}} + 1\right)^2} = -0.109\frac{1}{\Omega}$

$k_{cp} := \frac{I_c \cdot V_{ac}}{V_{cp}^2 \cdot \left(\frac{V_{ac}}{V_{cp}} + 1\right)^2} = 0.221\frac{1}{\Omega}$

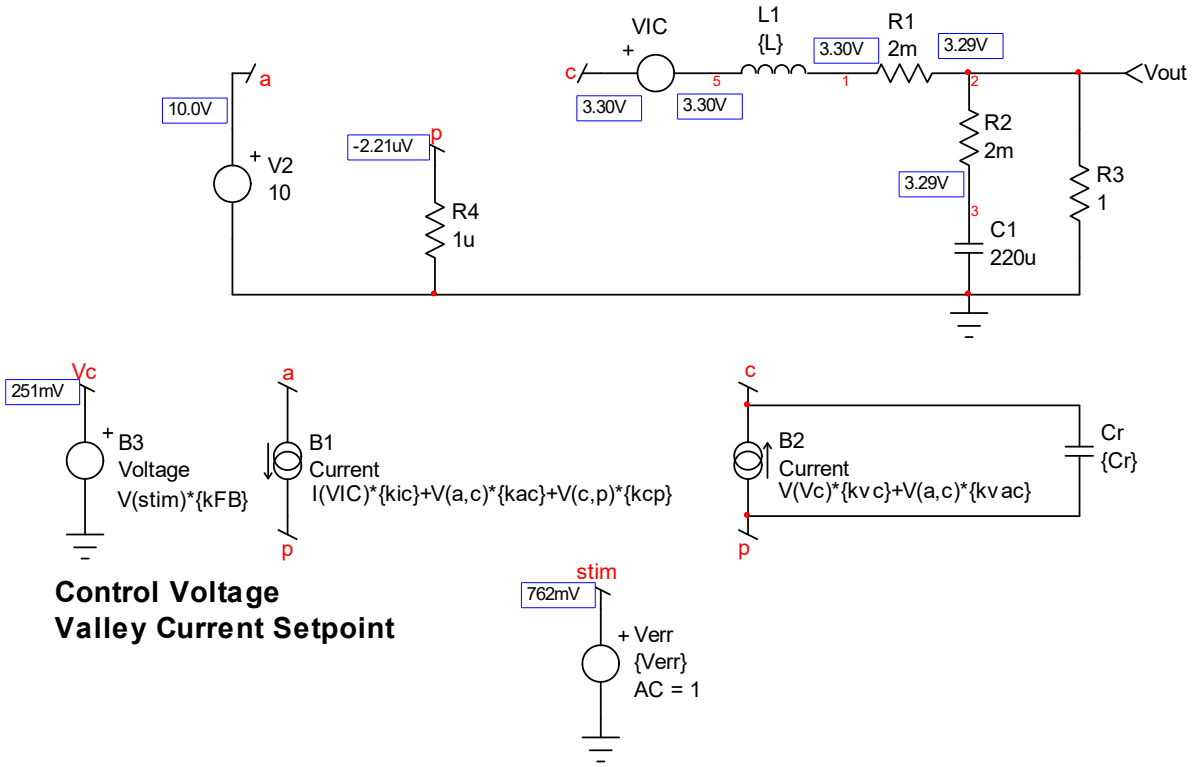
$k_{vc} := \frac{1}{R_i} = 12.5\frac{1}{\Omega}$ $k_{vac} := \frac{L_1 \cdot S_r \cdot V_{th}}{2 \cdot \left(L_1 \cdot S_r + R_i \cdot V_{ac}\right)^2} = 0.023\frac{1}{\Omega}$

Small-Signal Model

Parameters

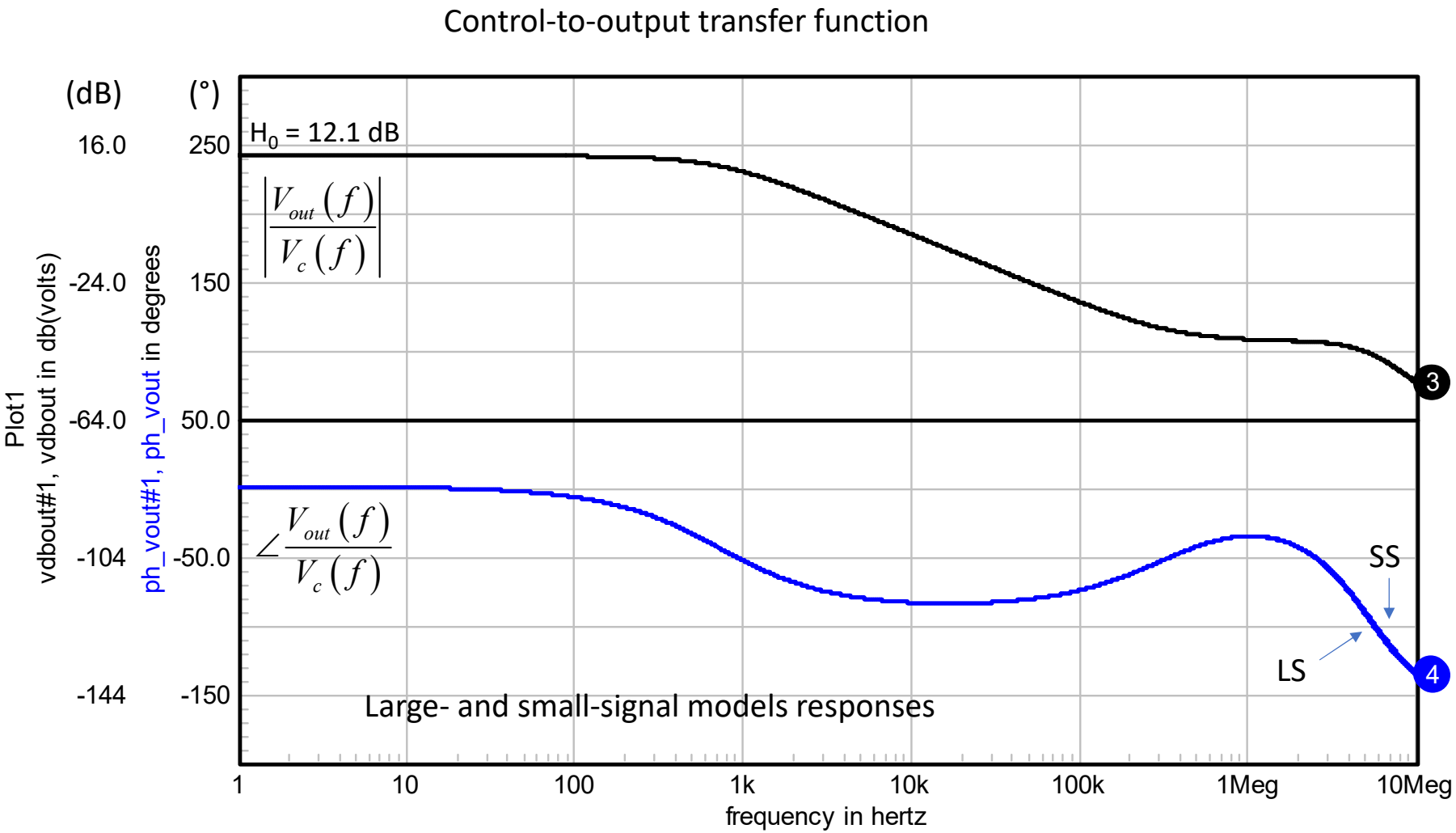
Vout=3.3
Vin=10
R=1
Ri=80m
L=2u
Sn=(Vin-Vout)/L
Ct=2p
Ichg=10u
Sr=Ichg/Ct
Vth=0.5
kFB=0.33
pi=3.14159
Verr=762m
Ic=Vout/R
Vac=Vin-Vout
Vcp=Vout

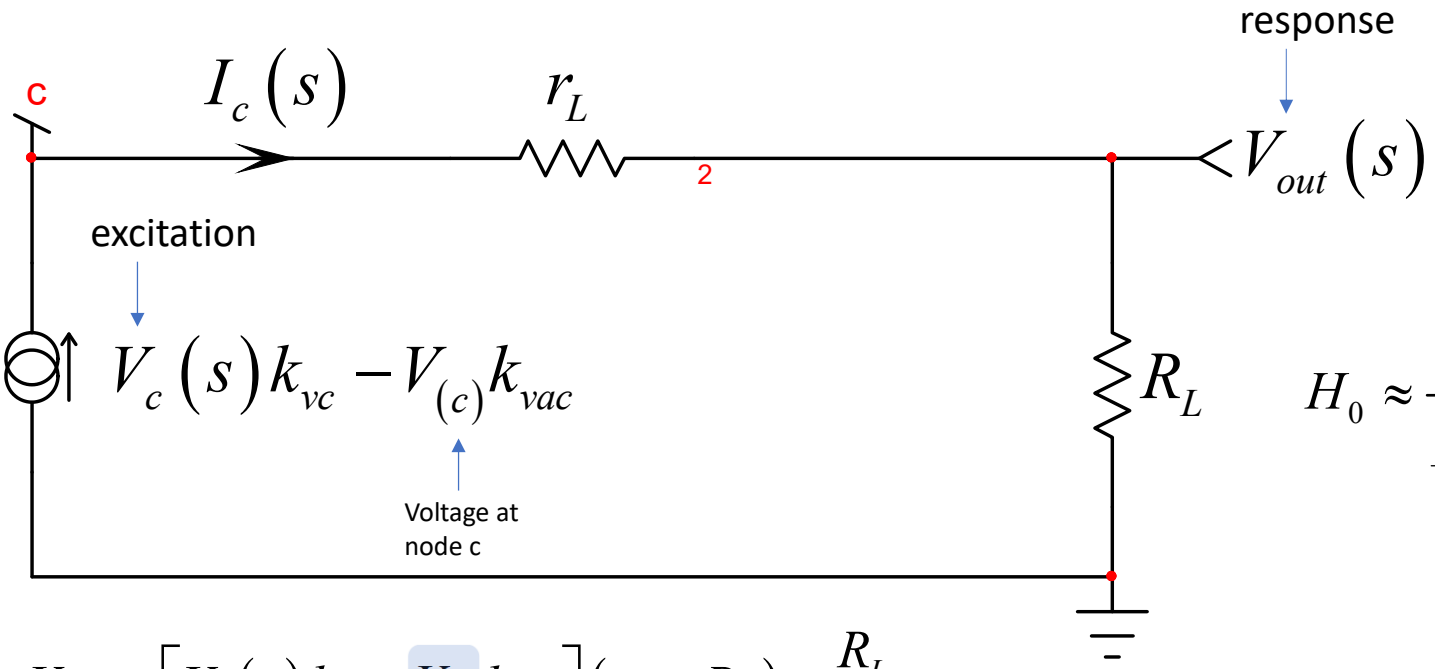
ton=Vth/(Sn*Ri+Sr)
cr=(1/{L})*(ton/{pi})^2
kic=1/(1+Vac/Vcp)
kac=-Ic/(Vcp*(Vac/Vcp+1)^2)
kcp=Ic*Vac/(Vcp^2*(Vac/Vcp+1)^2)
kvc=1/Ri
kvac=L*Sr*Vth/(2*(L*Sr+Ri*Vac)^2)



Control Voltage
Valley Current Setpoint

coefficients


Control-to-output transfer function
(dB)
(°)
16.0
250
H0 = 12.1 dB
|Vout(f) / Vc(f)|
-24.0
150
-64.0
50.0
-104
-50.0
∠Vout(f) / Vc(f)
SS
LS
-144
-150
Large- and small-signal models responses
3
4
1
10
100
1k
10k
100k
1Meg
10Meg
frequency in hertz
Plot1
vdbout#1, vdbout in db(volts)
ph_vout#1, ph_vout in degrees



$$\frac{k_{vc}}{k_{vac} + \frac{1}{R_L}} \cdot k_{FB} = 4.034$$

$$20 \cdot \log(H_0) = 12.115$$

$$\frac{1}{\frac{L_1 \cdot S_r \cdot V_{th}}{2 \cdot (L_1 \cdot S_r + R_i \cdot V_{ac})^2} + \frac{1}{R_L}} \cdot \frac{1}{R_i} \cdot k_{FB} = 4.034$$

$$H_0 \approx \frac{1}{\frac{LS_rV_{th}}{2(LS_r + R_iV_{ac})^2} + \frac{1}{R_L}} \frac{1}{R_i} k_{FB}$$

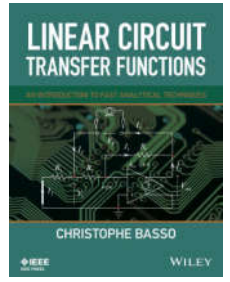
$$V_{out} = \left[V_c(s)k_{vc} - V_{(c)}k_{vac} \right](r_L + R_L)\frac{R_L}{r_L + R_L}$$

$$V_{(c)} = \left[V_c(s)k_{vc} - V_{(c)}k_{vac} \right](r_L + R_L)$$

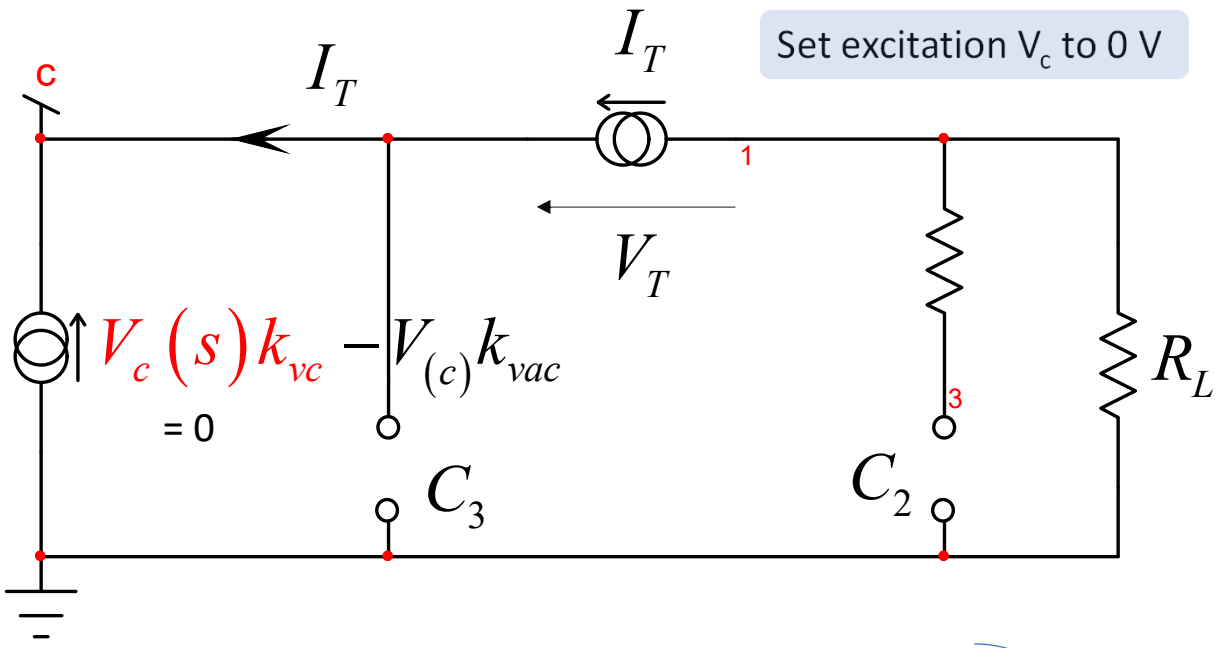
$$V_{(c)} = \frac{V_c(s)k_{vc}(r_L + R_L)}{k_{vac}(R_L + r_L) + 1}$$

$$H_0 = \frac{R_L k_{vc}}{k_{vac}(R_L + r_L) + 1} k_{FB} \approx \frac{k_{vc}}{k_{vac} + \frac{1}{R_L}} k_{FB}$$

Determination of the small-signal transfer function using the FACTs



τ_1



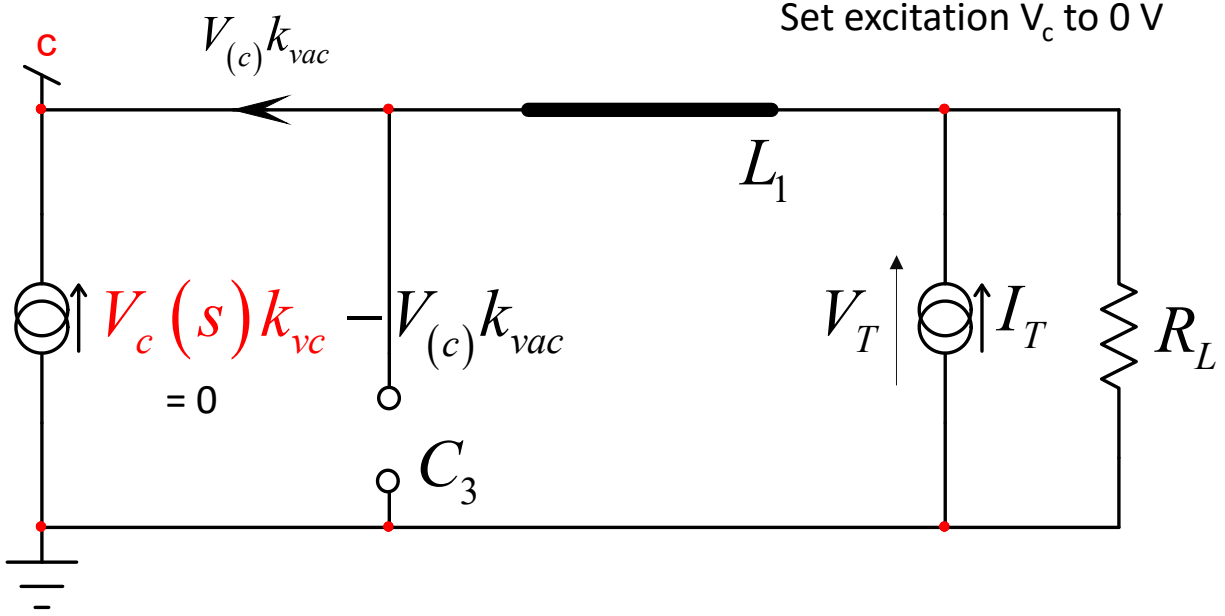
$$V_{(1)} = -I_T R_L \qquad -V_{(c)} k_{vac} = -I_T \qquad V_{(c)} = \frac{I_T}{k_{vac}}$$

$$V_T = V_{(c)} - V_{(1)} = \frac{I_T}{k_{vac}} + I_T R_L = I_T \left(\frac{1}{k_{vac}} + R_L \right)$$

$$\tau_1 = \frac{L}{\frac{1}{k_{vac}} + R_L}$$

Set excitation V_c to 0 V

τ_2



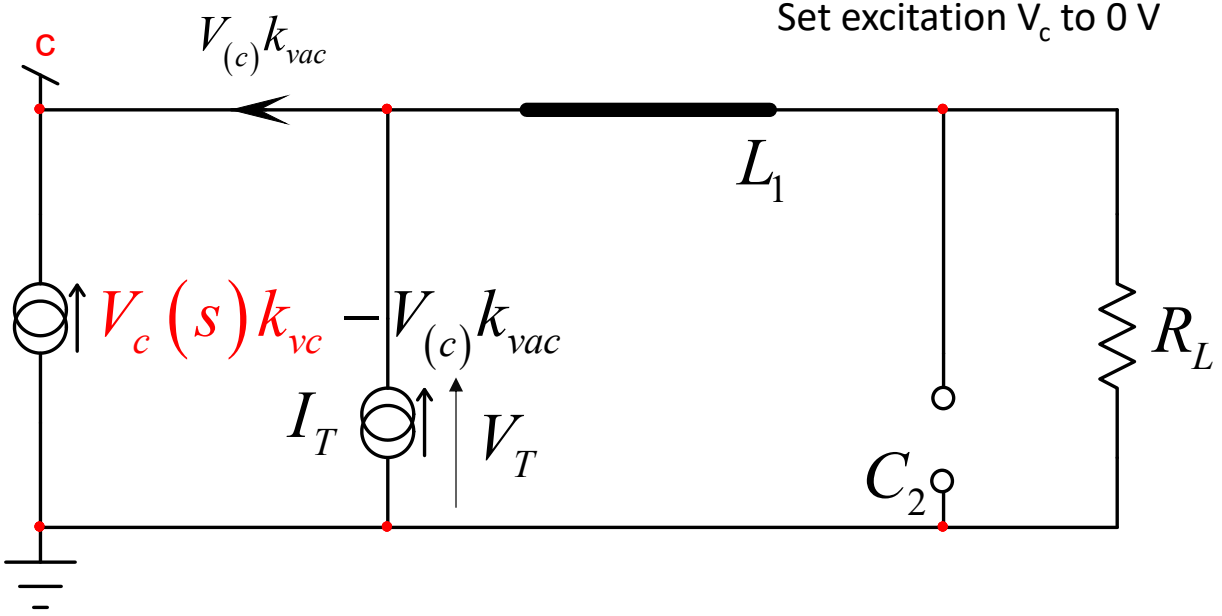
$$V_T = R_L\left(I_T - V_{(c)}k_{vac}\right) = R_L\left(I_T - V_T k_{vac}\right) = R_L I_T - R_L V_T k_{vac}$$

$$V_T\left(1 + R_L k_{vac}\right) = R_L I_T$$

$$\tau_2 = C_2 \frac{R_L}{1 + R_L k_{vac}}$$

Set excitation V_c to 0 V

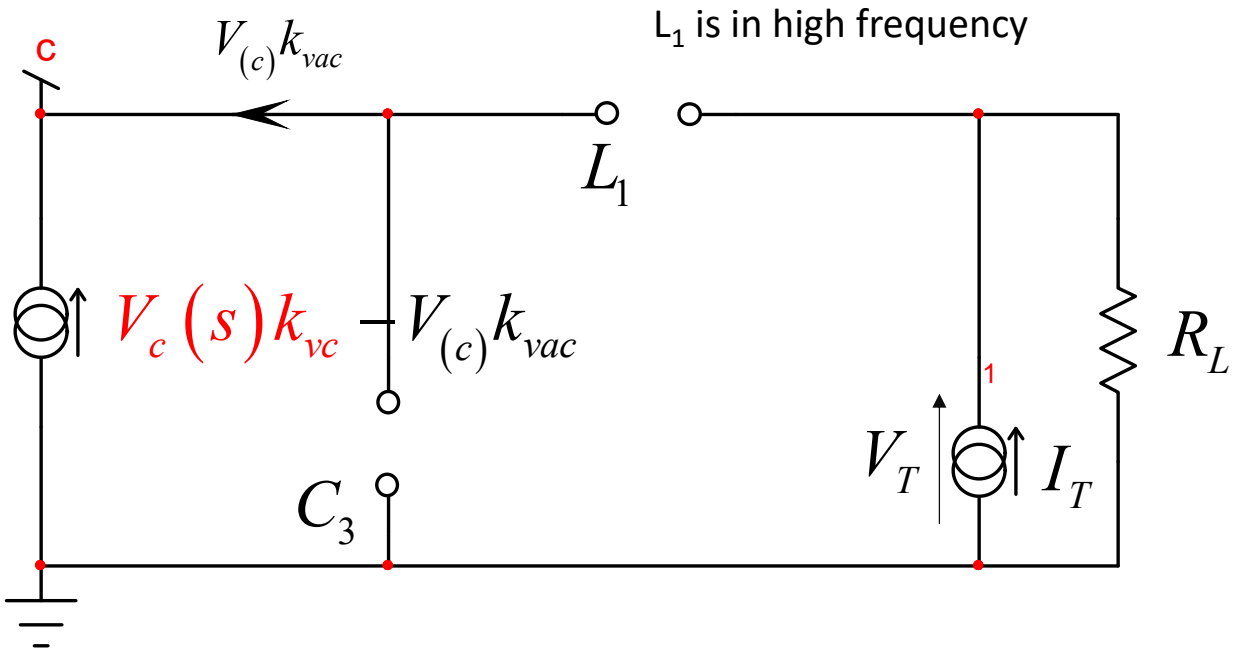
τ_3



$$\tau_3 = C_3 \frac{R_L}{1 + R_L k_{vac}}$$

$$b_1 = \tau_1 + \tau_2 + \tau_3 = \frac{L_1}{\frac{1}{k_{vac}} + R_L} + (C_2 + C_3)\frac{R_L}{1 + R_L k_{vac}}$$

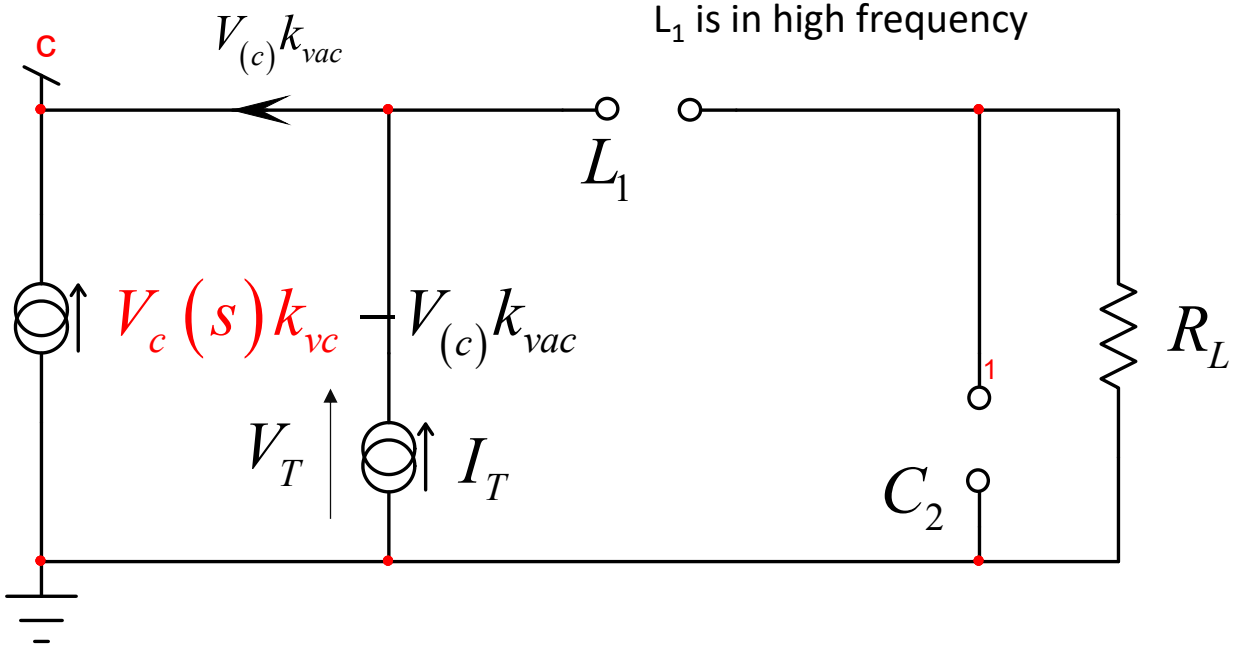
τ_2^1



L_1 is in high frequency

$$\tau_2^1 = R_L C_2$$

Set excitation V_c to 0 V



L_1 is in high frequency

Set excitation V_c to 0 V

$$\tau_3^1$$

$$V_{(c)} = V_T \qquad V_{(c)}k_{vac} = I_T$$

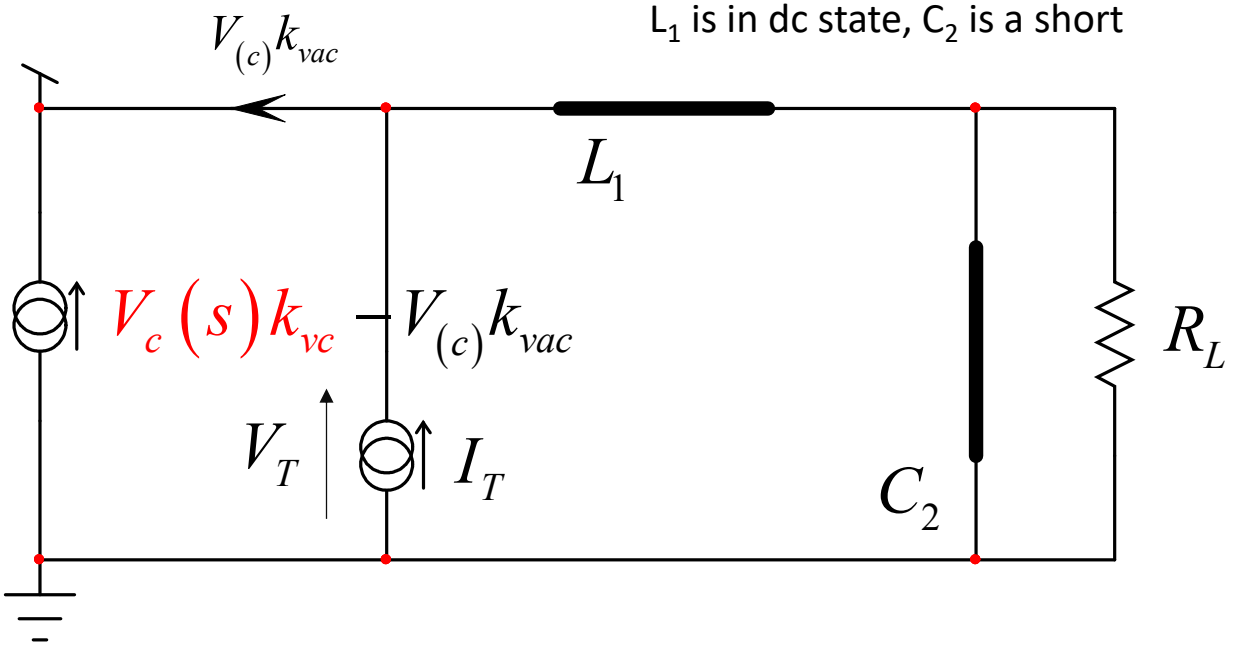
$$\frac{V_T}{I_T} = \frac{1}{k_{vac}}$$

$$\Rightarrow \quad \tau_3^1 = \frac{C_3}{k_{vac}}$$

τ_3^2

L_1 is in dc state, C_2 is a short

Set excitation V_c to 0 V



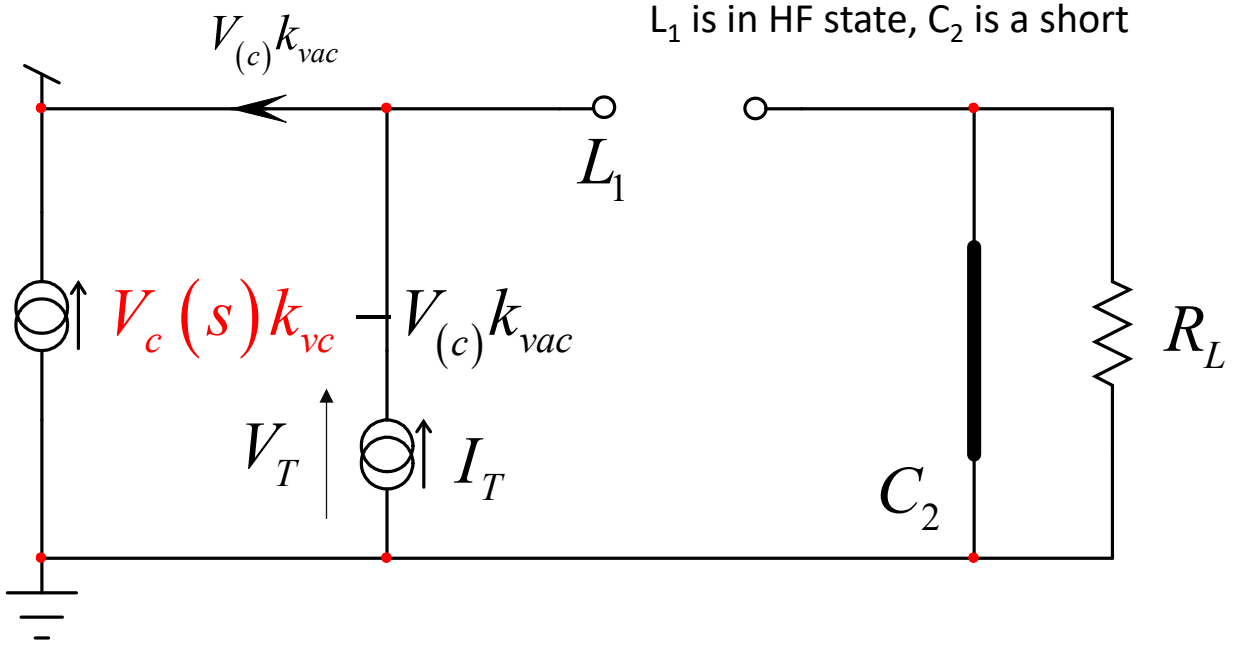
$$\tau_3^2 = C_3 \cdot 0$$

$$b_2 = \tau_1\tau_2^1 + \tau_1\tau_3^1 + \tau_2\tau_3^2 = \frac{L_1}{\frac{1}{k_{vac}} + R_L}\left(C_2 R_L + \frac{C_r}{k_{vac}}\right)$$

τ_3^{12}

L_1 is in HF state, C_2 is a short

Set excitation V_c to 0 V

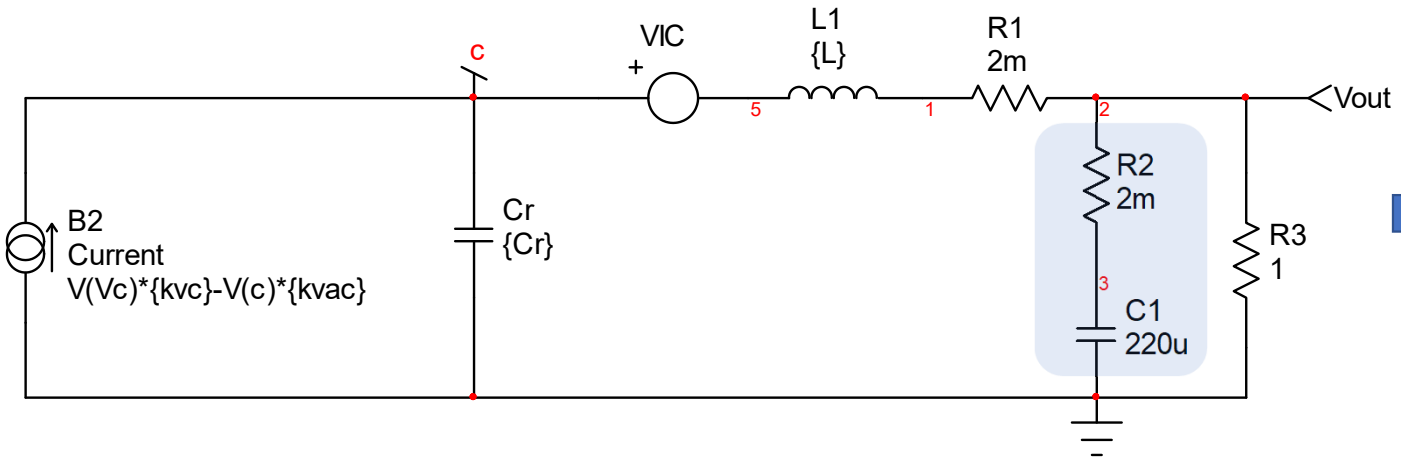


$$V_{(c)} = V_T \qquad V_{(c)}k_{vac} = I_T$$

$$\frac{V_T}{I_T} = \frac{1}{k_{vac}}$$

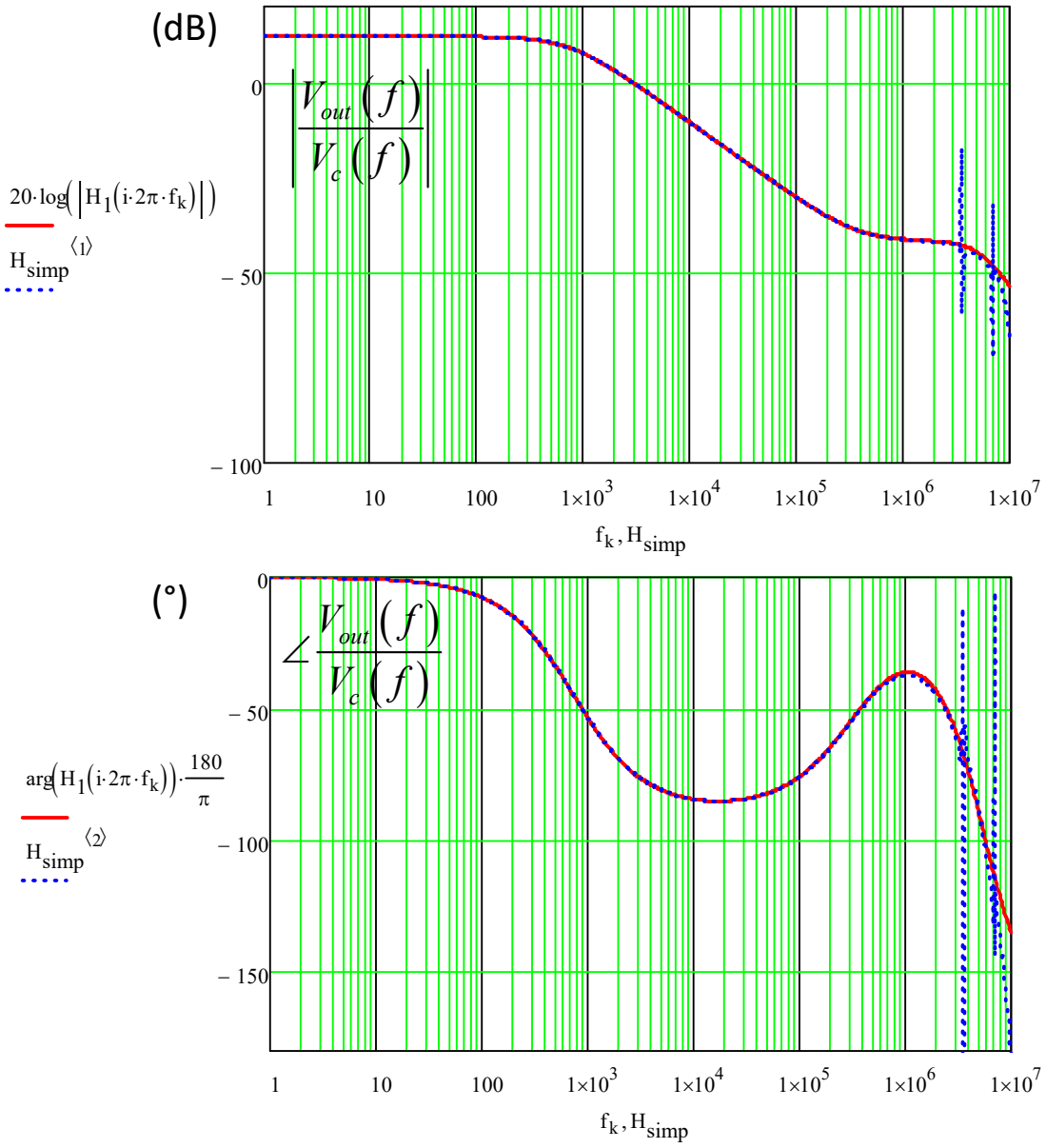
$$b_3 = \tau_1\tau_2^1\tau_3^{12} = \frac{L_1}{\frac{1}{k_{vac}} + R_L} C_2 R_L \frac{C_r}{k_{vac}}$$

$$\tau_3^{12} = \frac{C_3}{k_{vac}}$$



$$\omega_z = \frac{1}{r_C C_2}$$

$$H(s) = H_0 \frac{1 + \frac{s}{\omega_z}}{1 + sb_1 + s^2 b_2 + s^3 b_3}$$



Comparisons of responses between SIMPLIS and Mathcad.

$$H(s) = H_0 \frac{1+\frac{s}{\omega_z}}{1+sb_1+s^2b_2+s^3b_3} \approx H_0 \frac{1+\frac{s}{\omega_z}}{1+\frac{s}{\omega_p}} \frac{1}{1+\frac{s}{\omega_1 Q}+\left(\frac{s}{\omega_1}\right)^2} \qquad \omega_p = \frac{1}{b_1} \quad Q \approx \frac{2}{\pi} \quad \omega_1 \approx \frac{\pi}{t_{on}}$$

$$\omega_p = \frac{2S_r{}^2L^2 + \left(R_L S_r V_{th} + 4R_i S_r V_{ac}\right)L + 2R_i{}^2 V_{ac}{}^2}{L^2\left(S_r V_{th} + 2C_2 R_L S_r{}^2 + 2C_r R_L S_r{}^2\right) + L\left(4C_2 R_L R_i S_r V_{ac} + 4C_r R_L R_i S_r V_{ac}\right) + 2R_L R_i{}^2 V_{ac}{}^2\left(C_r + C_2\right)}$$

$$\omega_p \approx \frac{2S_r{}^2L^2 + \left(R_L S_r V_{th} + 4R_i S_r V_{ac}\right)L + 2R_i{}^2 V_{ac}{}^2}{L^2 S_r V_{th} + 2C_2 R_L S_r{}^2 + L4C_2 R_L R_i S_r V_{ac} + 2R_L R_i{}^2 V_{ac}{}^2 C_2}$$

$$\omega_{pp} := \frac{2\cdot S_r{}^2\cdot L_1{}^2 + \left(R_L\cdot S_r\cdot V_{th} + 4\cdot R_i\cdot S_r\cdot V_{ac}\right)\cdot L_1 + 2\cdot R_i{}^2\cdot V_{ac}{}^2}{\left(S_r\cdot V_{th} + 2\cdot C_2\cdot R_L\cdot S_r{}^2 + 2\cdot C_r\cdot R_L\cdot S_r{}^2\right)\cdot L_1{}^2 + \left(4\cdot C_2\cdot R_L\cdot R_i\cdot S_r\cdot V_{ac} + 4\cdot C_r\cdot R_L\cdot R_i\cdot S_r\cdot V_{ac}\right)\cdot L_1 + 2\cdot R_L\cdot R_i{}^2\cdot V_{ac}{}^2\cdot\left(C_2 + C_r\right)} = 4.647\times 10^3\,\frac{1}{s} \qquad \omega_p := \frac{1}{b_1} = 4.647\times 10^3\,\frac{1}{s}$$

$$\frac{2\cdot L_1{}^2\cdot S_r{}^2 + 4\cdot L_1\cdot R_i\cdot S_r\cdot V_{ac} + R_L\cdot V_{th}\cdot L_1\cdot S_r + 2\cdot R_i{}^2\cdot V_{ac}{}^2}{2\cdot C_2\cdot R_L\cdot L_1{}^2\cdot S_r{}^2 + V_{th}\cdot L_1{}^2\cdot S_r + 4\cdot C_2\cdot R_L\cdot L_1\cdot R_i\cdot S_r\cdot V_{ac} + 2\cdot C_2\cdot R_L\cdot R_i{}^2\cdot V_{ac}{}^2} = 4.647\times 10^3\,\frac{1}{s}$$

Comparison between SIMPLIS and the simplified expression.