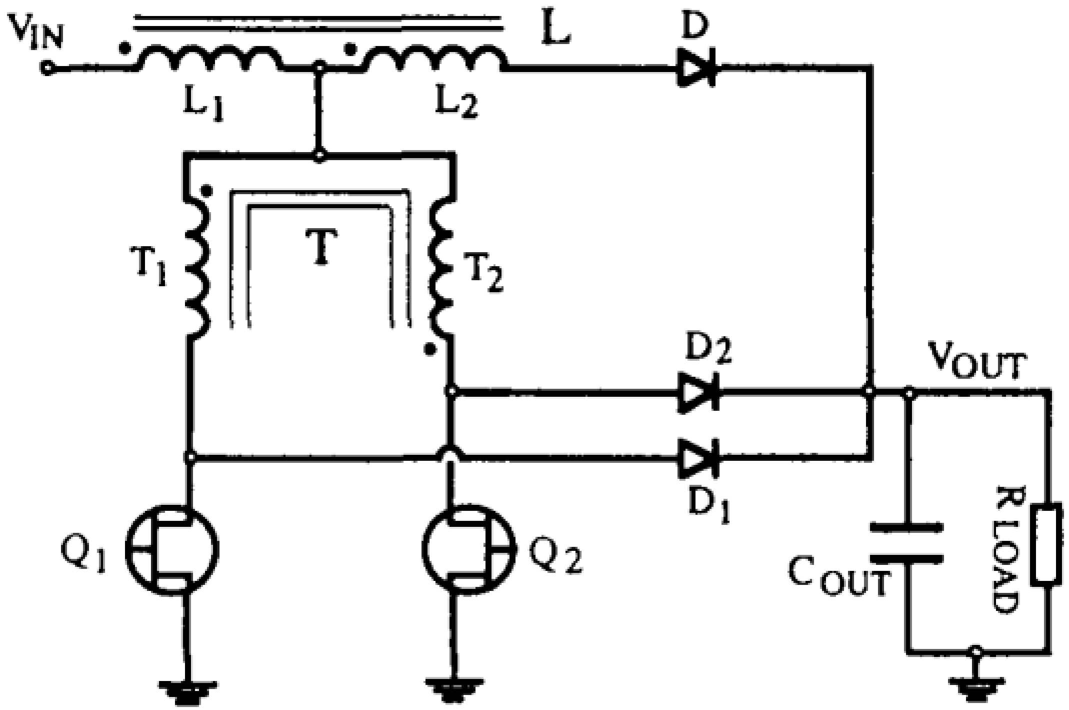
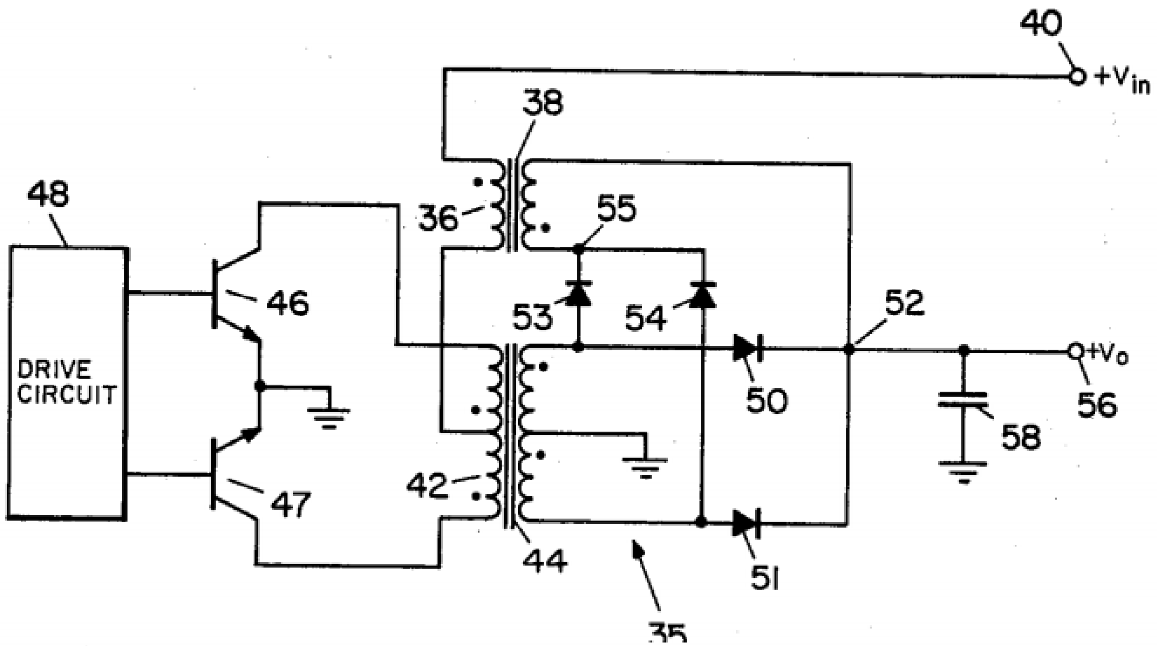




United States Patent [19] [11] **4,318,166**

Bloom [45] **Mar. 2, 1982**

The original converter was documented by A.H. Weinberg in 1974. Below is an excerpt from *A High-Power, High-Frequency, Dc-to Dc Converter for Space applications*, *PESC 1992*

This is the improved Weinberg converter structure patented by Ed. Bloom in 1982: 4,318,166.

** Breadboard efficiency between 95 to 97% at from 500W to 1KW output power.*

** Continuous output current with small current ripple.*

** A Boost Regulator without the right half-plane zero effect giving a high bandwidth response.*

** Low switching losses (typically 1% at a switching frequency of 350kHz.).*

** Conductance control produces typical first order response.*

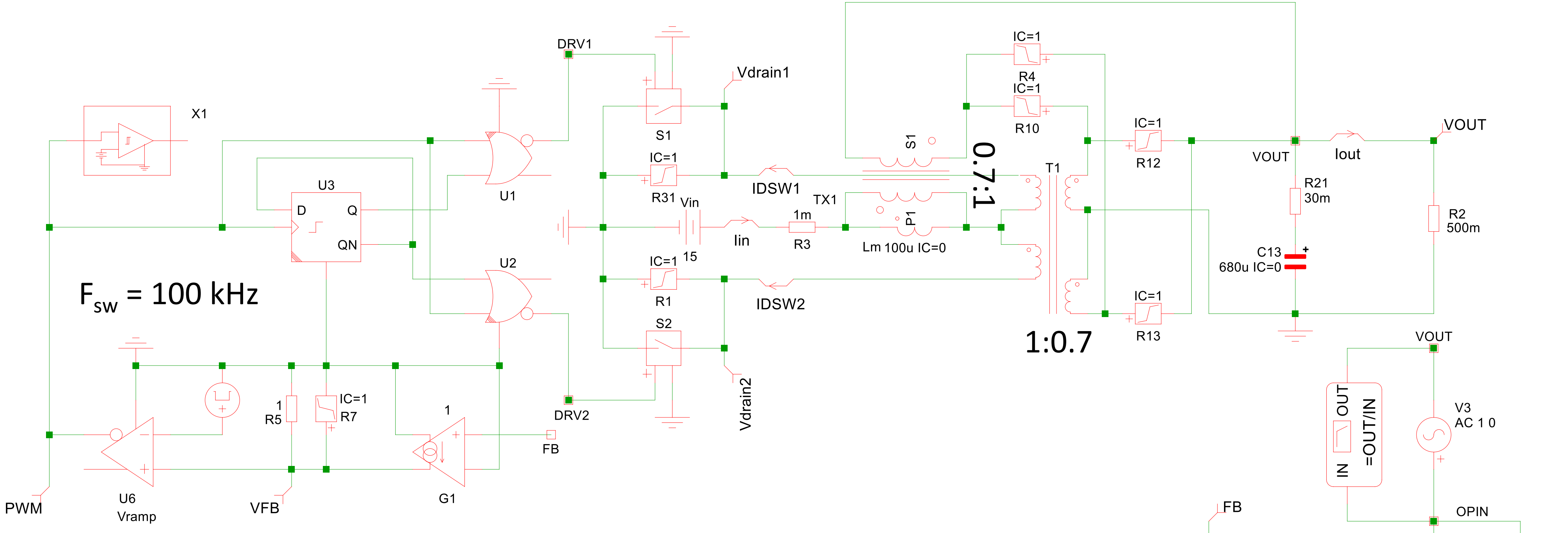
** Wide bandwidth voltage regulation loop (10KHz, with 80º phase margin) giving superior transient response and reduced output filtering.*

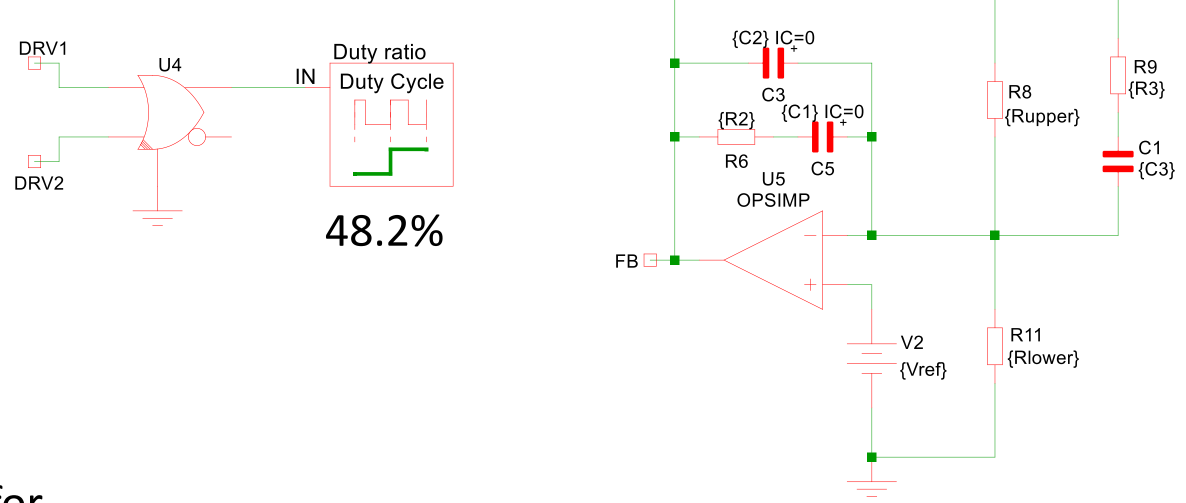
Alan H. Weinberg

Weinberg Electronics Innovations Limited, UK

Alan Weinberg now retired, spent 23 years working as a senior power electronics engineer at the European Space Agency. During this period, he invented many new concepts in power electronics, the most important being conductance control voltage regulation and the sequential switching shunt regulator (S3R) for the control of solar cell arrays. He is also perhaps better known for the Weinberg converter.

Christophe Basso – August 2024 – Rev 0.1

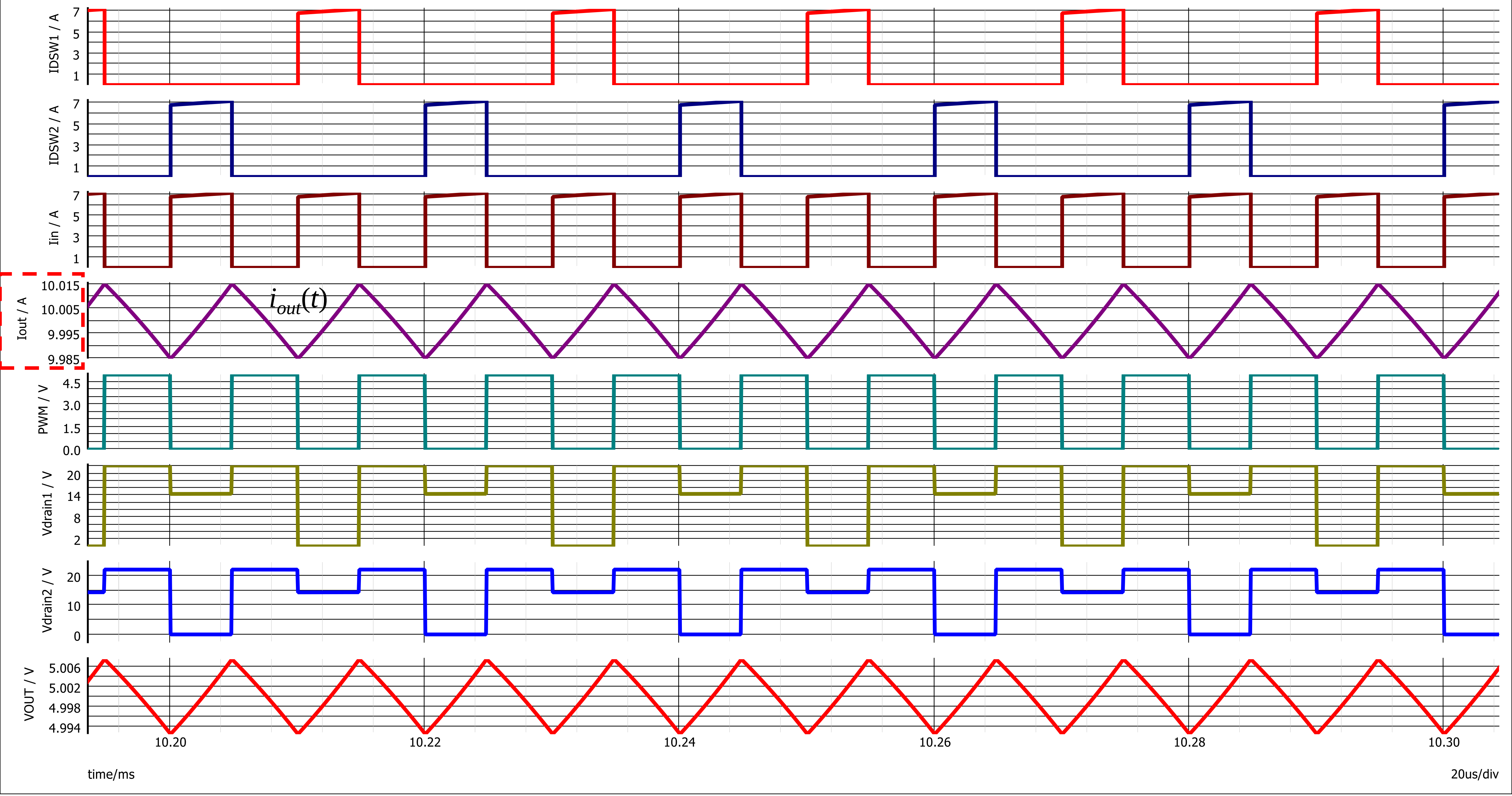




This is a fixed-frequency voltage-mode-controlled Weinberg converter delivering 5 V 10 A from a 15-V source. Enable the fixed load for ac analysis and disable the PWL source (right-click after selection) to see the transient response. Check Simulator>Edit Netlist (after preprocess) to see the calculated component values.

- Christophe Basso - Transfer Functions of Switching Converters -

SIMPLIS simulation model for a 5-V/10-A Weinberg converter supplied from a 15-V source. Turns ratio for push-pull and flyback transformers are identical at 700m.



SIMPLIS operating point for a 15-V input source and 50-W/5-V output. Notice the almost dc output current (30 mA peak-to-peak for I_{out})

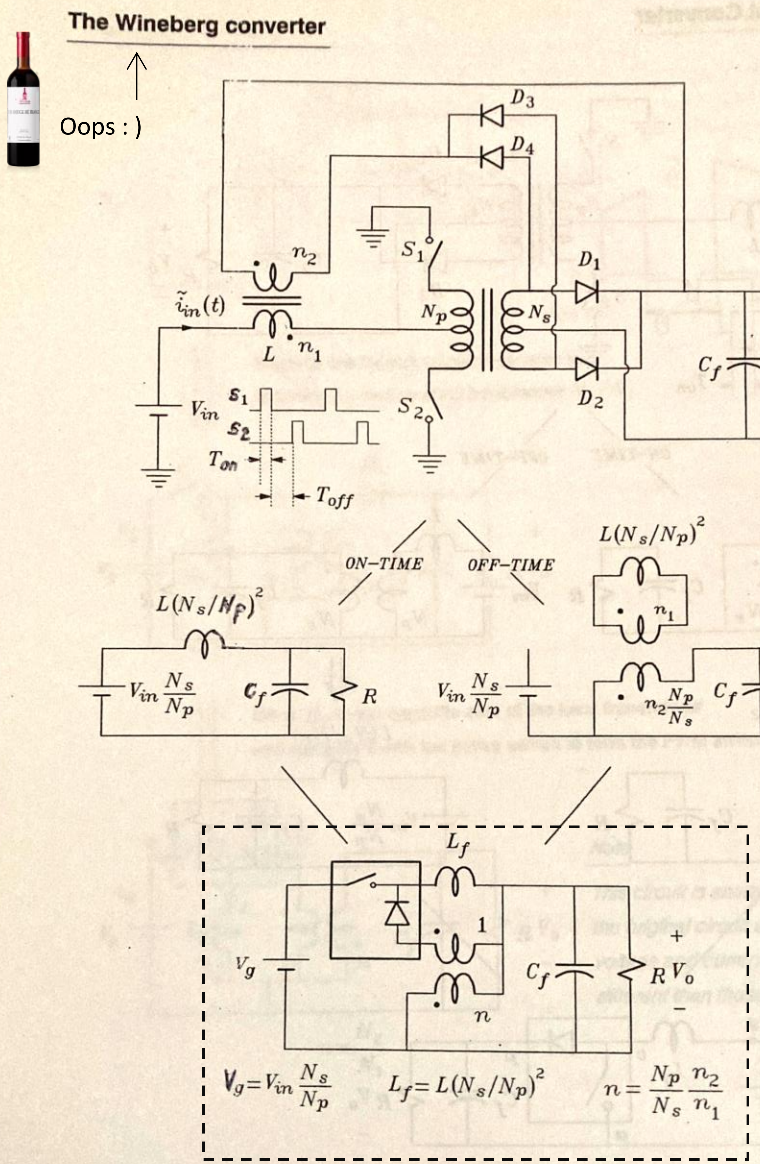
A three-day course on a circuit-oriented approach to the analysis and design of PWM dc-to-dc converters using the model of the PWM switch

Conducted by

Vatché Vorpérian

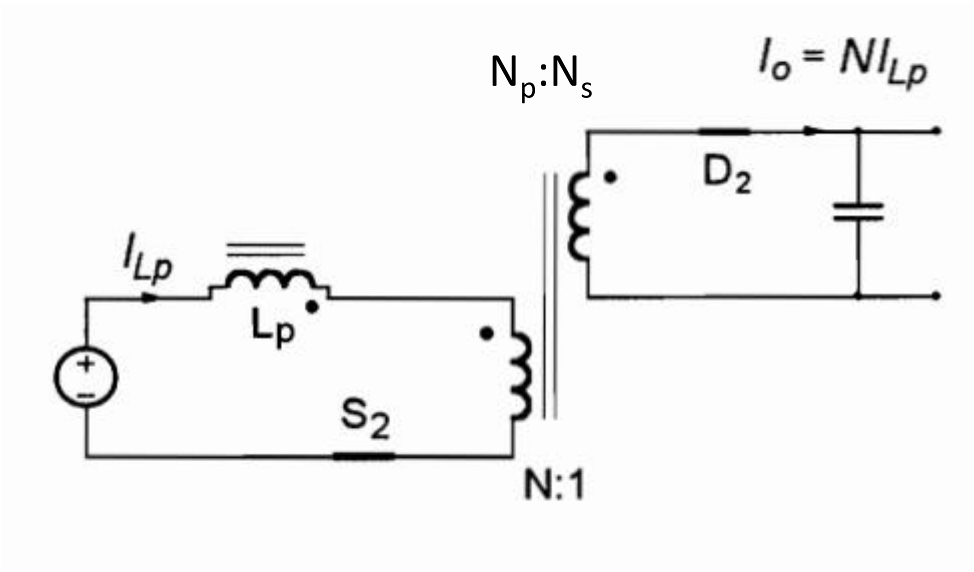
Jet Propulsion Laboratory
California Institute of Technology

The Weinberg converter can be modeled with the PWM switch model introduced by Dr. Vatché Vorpérian in 1986. I had the privilege to attend his course in 2004 in Toulouse whilst with onsemi. The distributed material did include an average schematic of the Weinberg converter as patented by Ed. Bloom but no transfer function derivation was included.



This is the averaged model of the Weinberg converter.

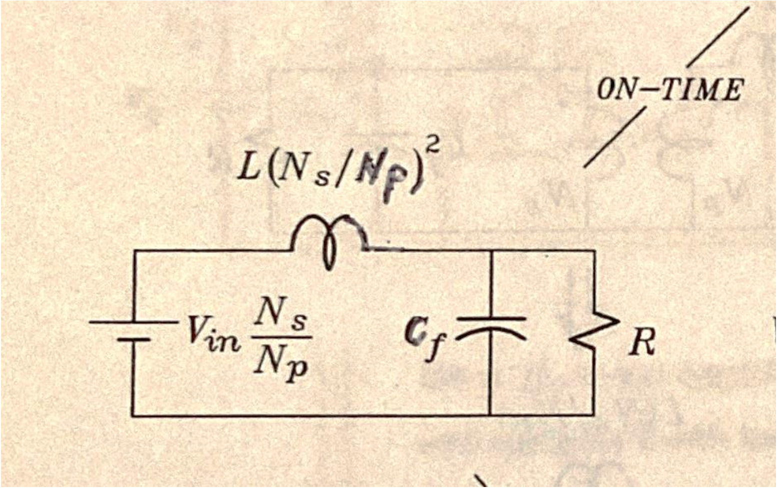
During the on-time:



Reflect L and V_{in} on the sec side:

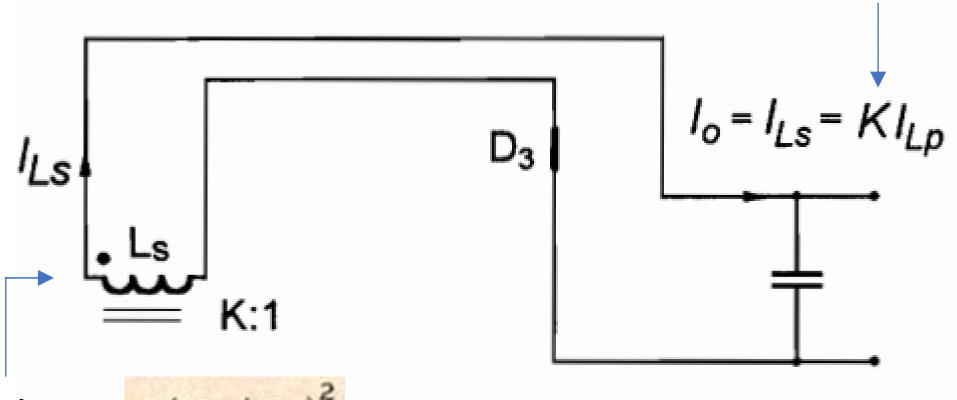
N is N_p/N_s

On average during t_{on}



During the off-time:

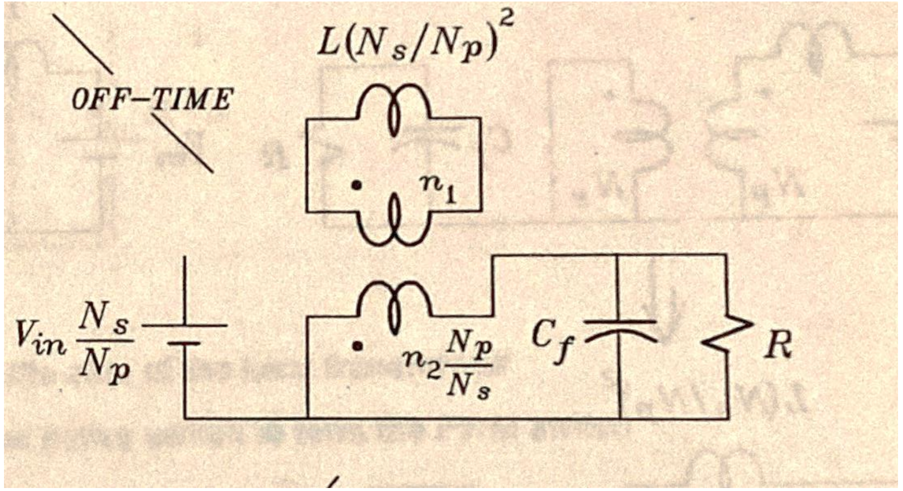
this is n_1/n_2



This is $L(N_s/N_p)^2$

You have the current circulating in the reflected inductance scaled by the flyback turns ratio

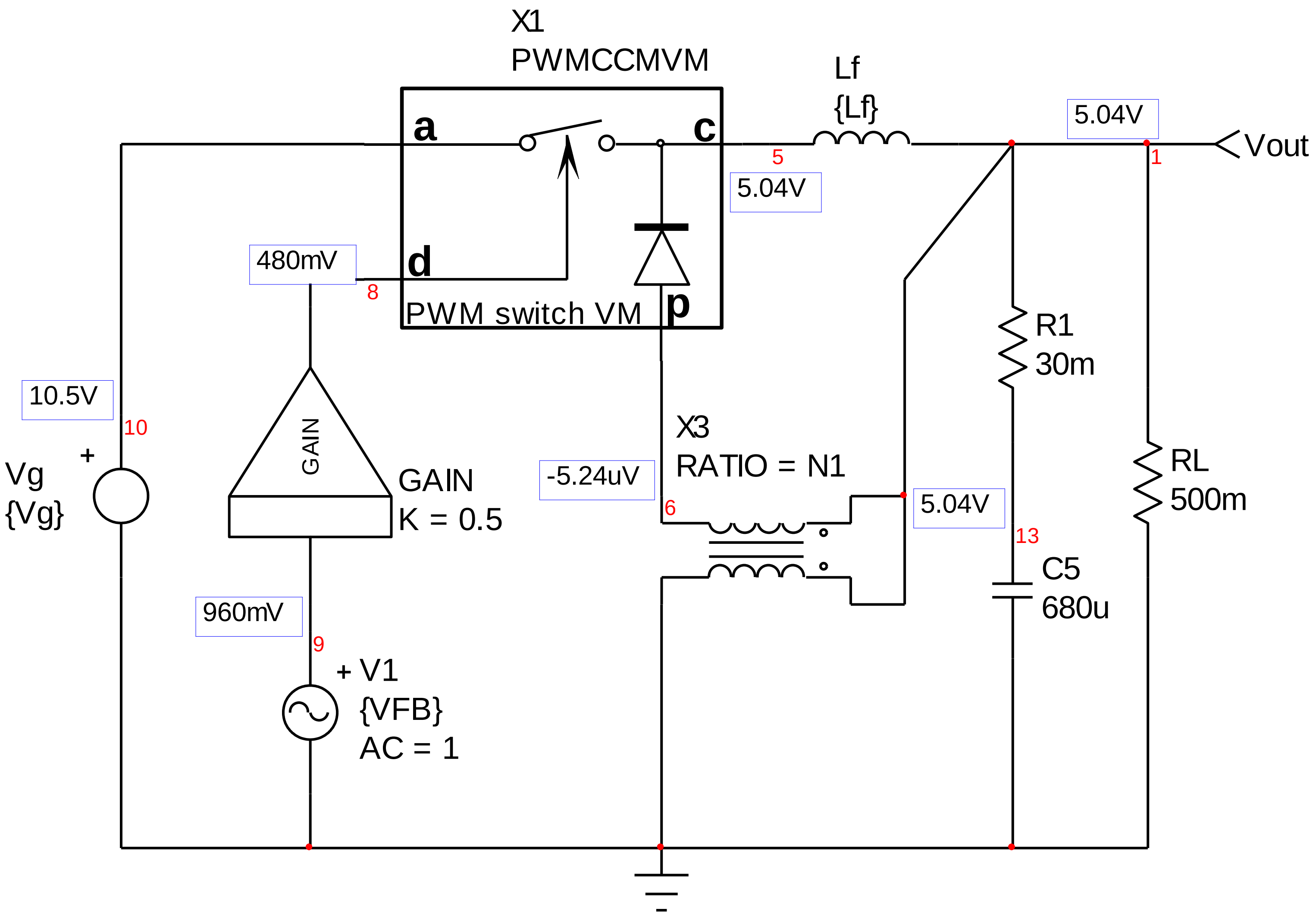
On average during t_{off}



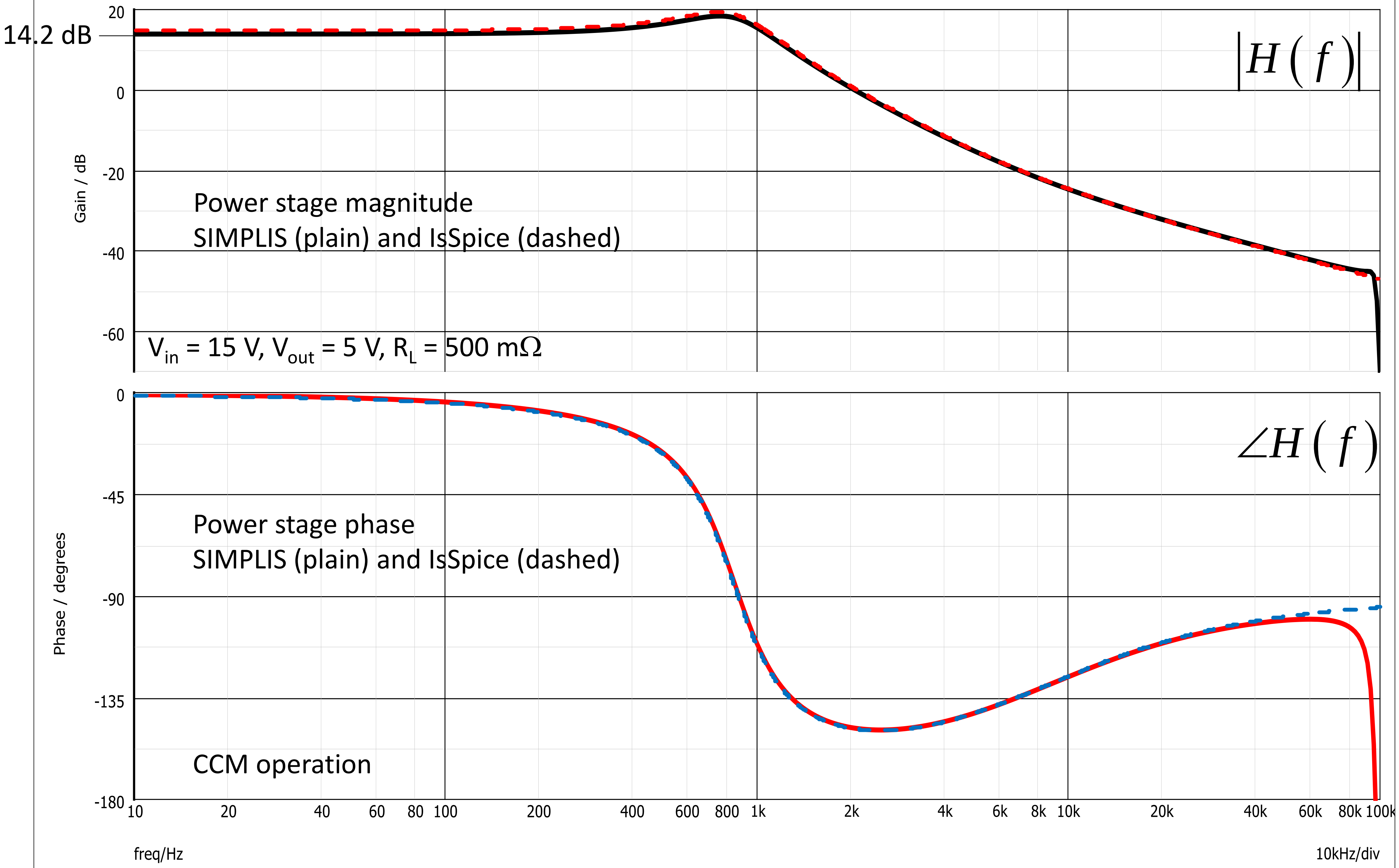
(from Goran Stojcic's thesis – see on the following slides)

parameters

Vin=15
L1=100u
Nfly=700m
Npush=700m
Lf=L1*Npush^2
Vg=Vin*Npush
N1=(1/Npush)*Nfly
D=0.48
VFB=960m



Averaged model with the PWM switch in CCM. The operating point confirms the SIMPLIS simulation which includes various drops linked to diodes forward voltages in particular.

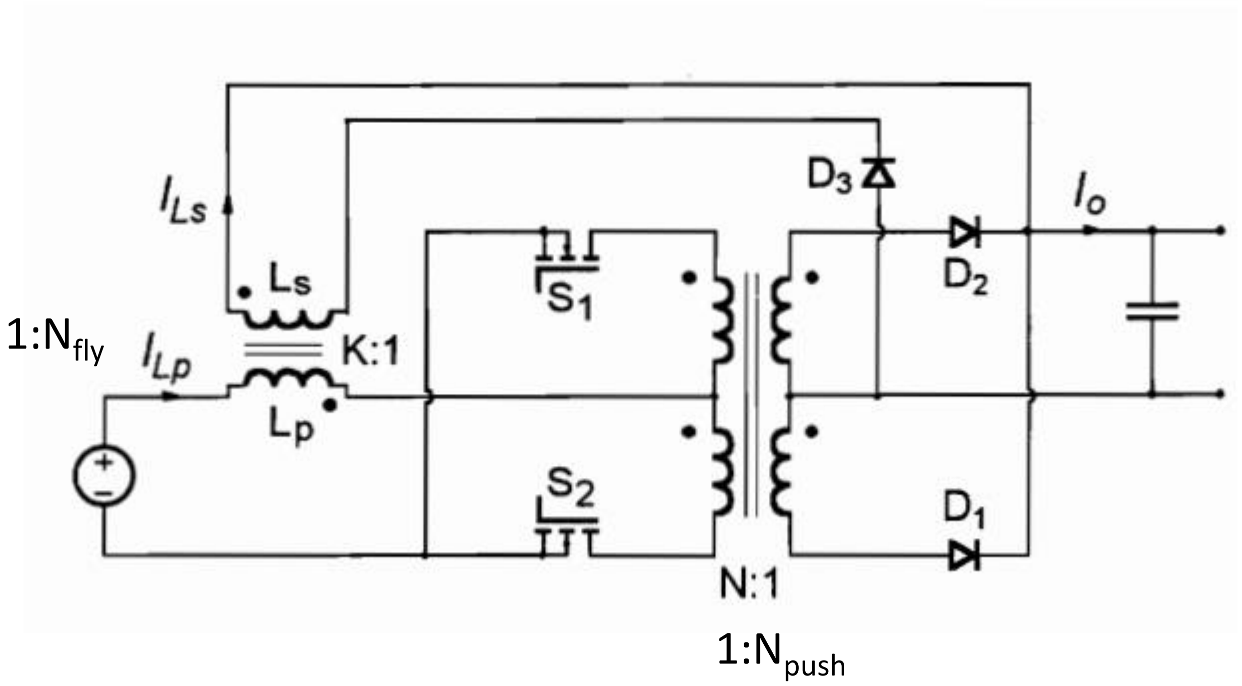


14.2 dB
|H(f)|
Power stage magnitude
SIMPLIS (plain) and IsSpice (dashed)
Vin = 15 V, Vout = 5 V, RL = 500 mΩ
Gain / dB
20
0
-20
-40
-60
∠H(f)
Power stage phase
SIMPLIS (plain) and IsSpice (dashed)
CCM operation
Phase / degrees
0
-45
-90
-135
-180
10 20 40 60 80 100 200 400 600 800 1k 2k 4k 6k 8k 10k 20k 40k 60k 80k 100k
freq/Hz
10kHz/div

From Active-Clamp PWM Converters: Design-Oriented Analysis and Small-Signal Characterization, MSEE thesis from Goran Stojcic:

$$\frac{V_o}{V_{in}} = \frac{D}{N D + K D'}, \text{ and}$$

$$D = \frac{V_o K}{V_{in} - V_o (N - K)},$$



$V_{in} := 15V$ $\quad V_{out} := 5V$ $\quad V_p := 2V$ $\quad R_{load} := 0.5\Omega$ $\quad r_C := 0.03\Omega$

$N_{fly} := 0.7$ $\quad N_{push} := 0.7$ $\quad L_m := 100\mu H$ $\quad C_{out} := 680\mu F$

$L_f := L_m \cdot N_{push}^2 = 49 \cdot \mu H$ $\quad V_{ap} := 9.86843V$ $\quad I_c := 10.8542A$

$I_T := 1A$ $\quad N_1 := \frac{1}{N_{push}} \cdot N_{fly} = 1$

$$D_{10} := \frac{N_{push} \cdot V_{out}}{N_{push} \cdot V_{out} - N_{fly} \cdot V_{out} + N_{fly} \cdot N_{push} \cdot V_{in}} = 47.61905 \cdot \%$$

$D_1 := 47.619\%$

$$D_1 = \frac{N_{push} \cdot V_{out}}{N_{push} \cdot V_{out} - N_{fly} \cdot V_{out} + N_{fly} \cdot N_{push} \cdot V_{in}} \qquad V_{out} = \frac{D_1 \cdot N_{fly} \cdot N_{push} \cdot V_{in}}{N_{push} - D_1 \cdot N_{fly} + D_1 \cdot N_{push}}$$

$$H_0 = \frac{dV_{out}(D)}{dD}$$

This is the dc gain including the PWM modulator with a 2-V peak sawtooth (V_p).

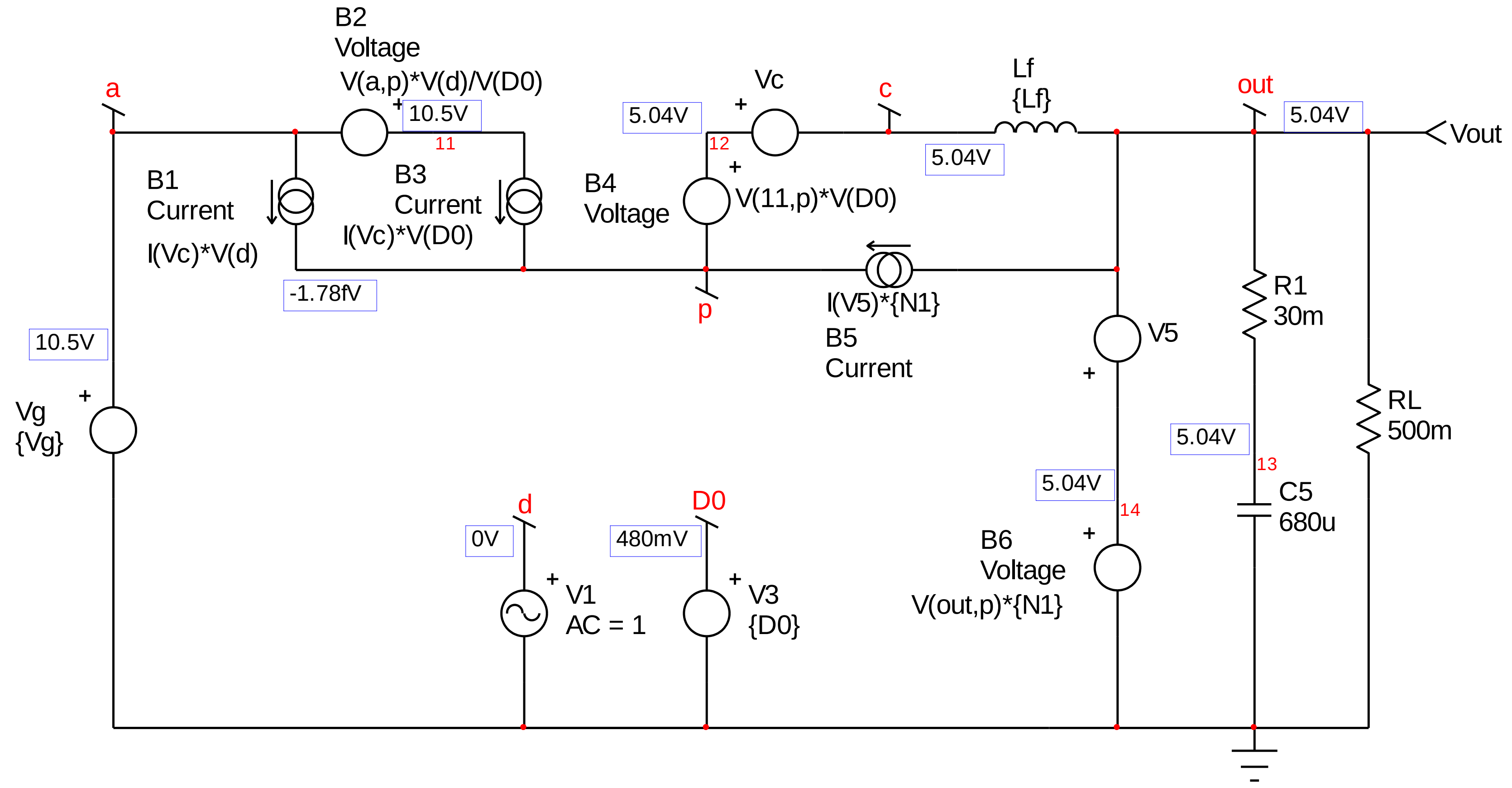
$$H_0 := \frac{1}{V_p} \cdot \frac{N_{fly} \cdot N_{push}^2 \cdot V_{in}}{\left(N_{push} + D_1 \cdot N_{fly} - D_1 \cdot N_{push}\right)^2} = 5.25$$

$20 \cdot \log(H_0) = 14.40319$ dB

SIMPLIS gives 14.2 dB

parameters

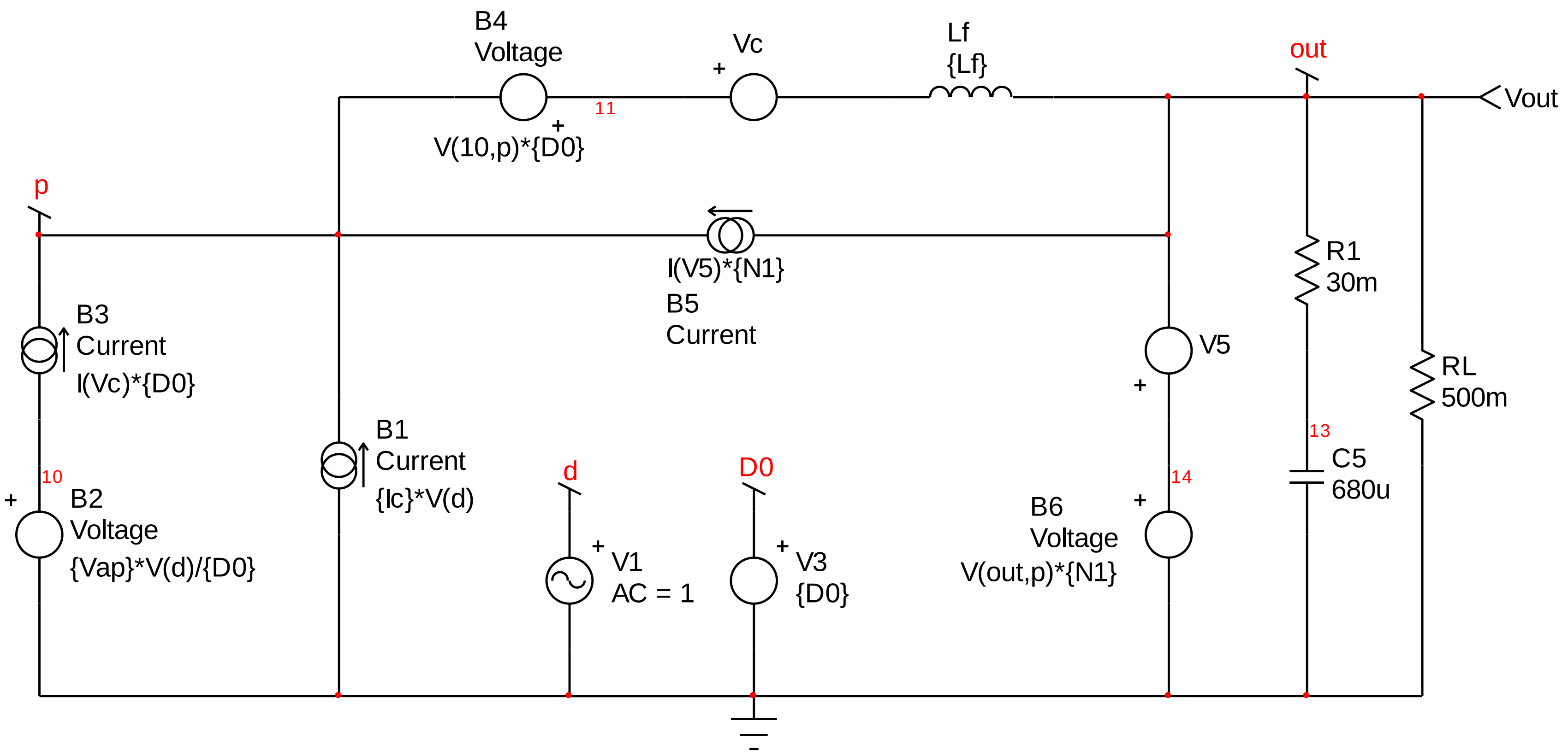
Vin=15
L1=100u
Nfly=700m
Npush=700m
Lf=L1*Npush^2
Vg=Vin*Npush
N1=(1/Npush)*Nfly
D0=0.48



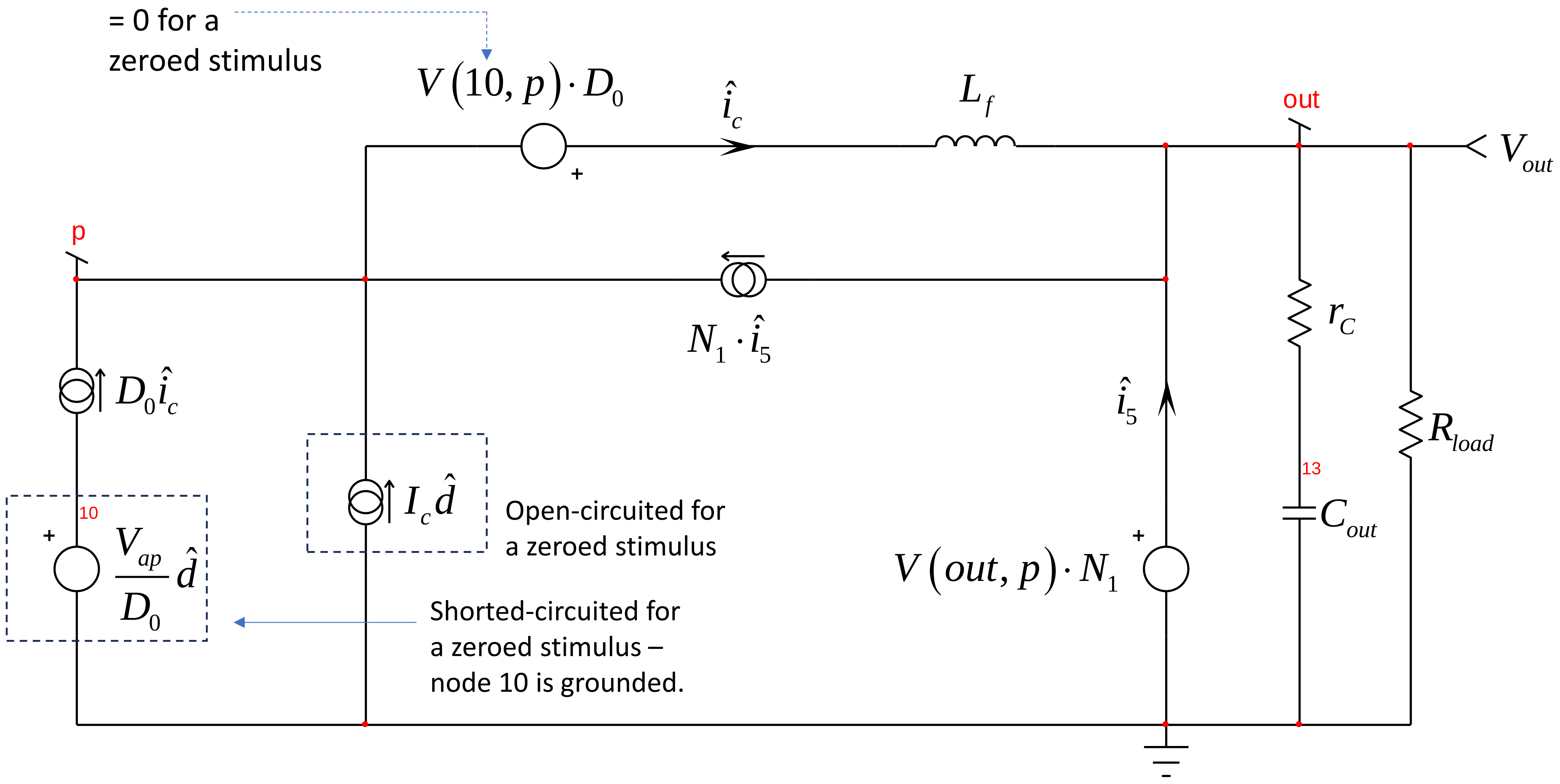
This is the small-signal version of the Weinberg converter operated in voltage-mode control. The dc operating point is still present, I can freeze the static coefficients and zero the input source to keep ac contributors only.

parameters

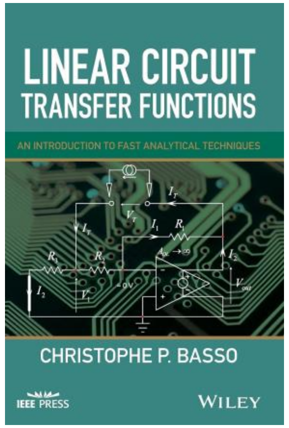
Vin=15
L1=100u
Nfly=700m
Npush=700m
Lf=L1*Npush^2
Vg=Vin*Npush
N1=(1/Npush)*Nfly
D0=0.48
Ic=10.08
Vap=10.5



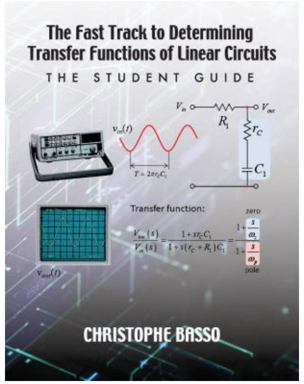
It is the final ac small-signal equivalent circuit of the Weinberg converter. The current in the c terminal as well as the ap voltages were determined via a simulated bias point analysis. Next step is to redraw the circuit with a zeroed stimulus for determining poles. Once this is done, a NDI will help obtain the zeroes of the transfer function.



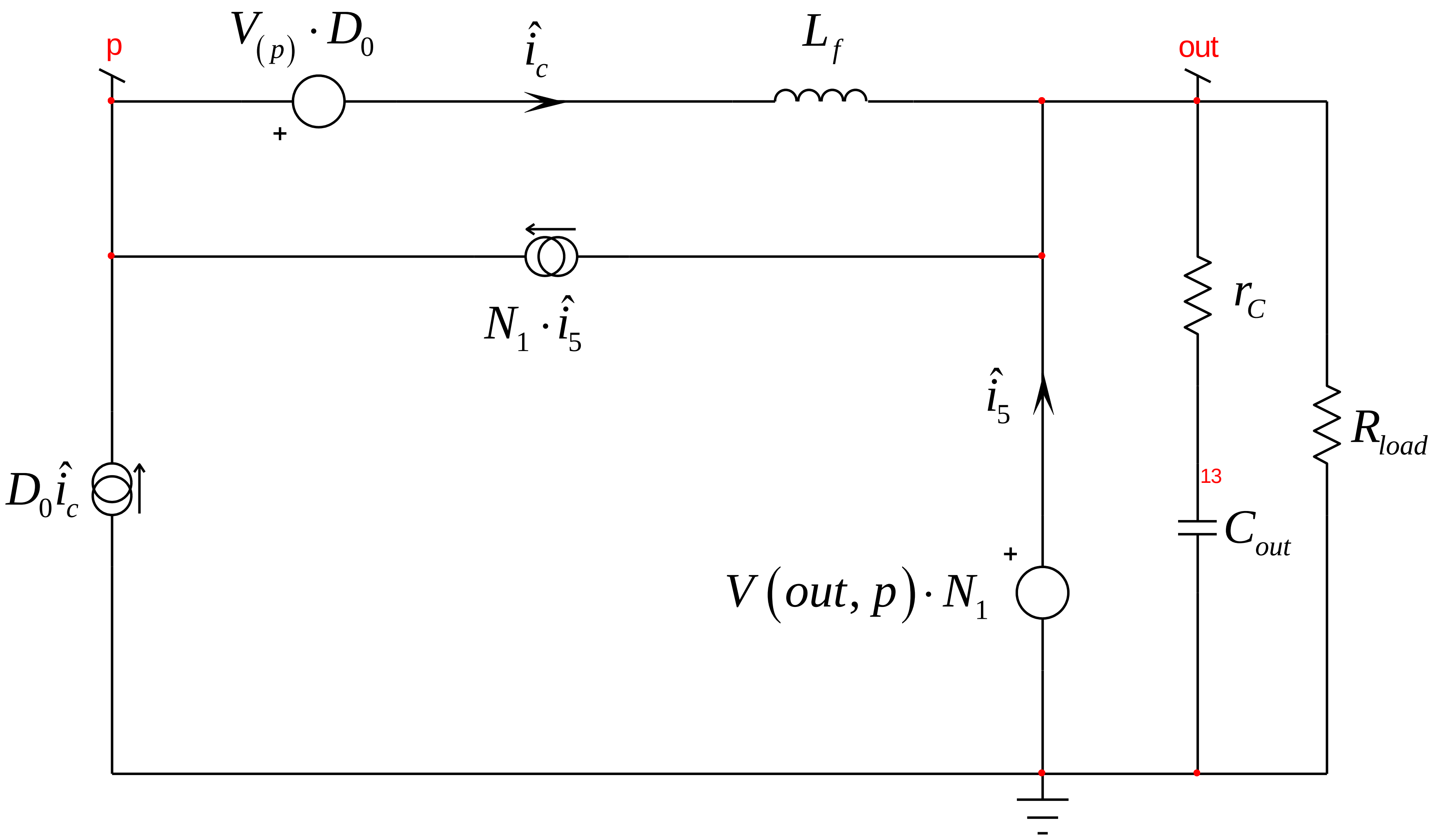
For the control-to-output transfer function, we are going to turn the stimulus off – $\hat{d}$ is zeroed – and we can further simplify the circuitry for determining the terms b_1 and b_2.



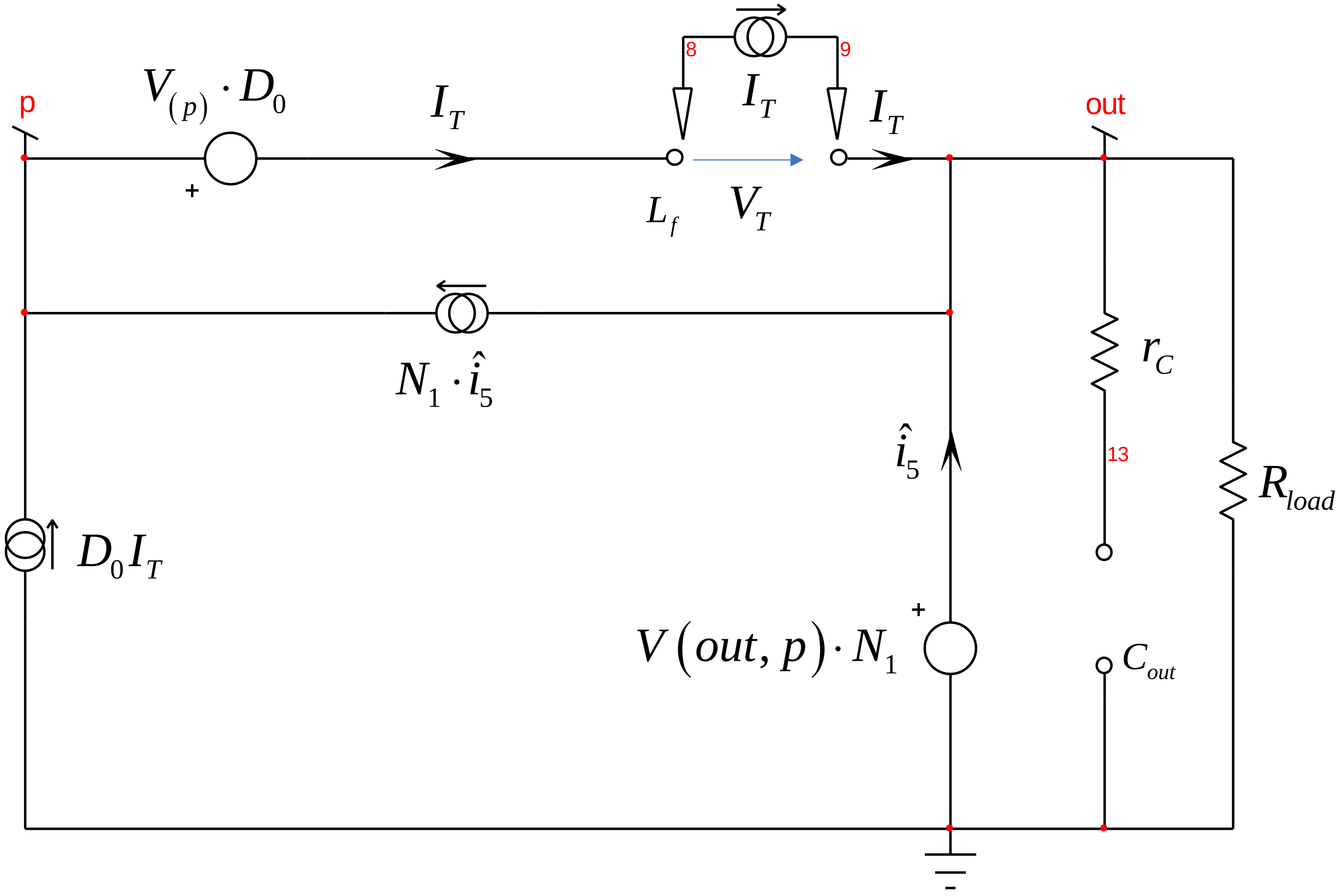
Linear Circuits Transfer Functions – Christophe Basso, Wiley, 2016



The Fast Track to Determining Transfer Functions – Christophe Basso, Faraday Press, 2023



We can now apply the fast analytical circuits techniques or FACTs by determining the resistance R driving the inductance L_f and the output capacitor C_{out}.



$$i_5 = \frac{I_T(1 - D_0)}{N_1}$$

$$V_T = V_{(out)} - V_{(p)}(1 - D_0)$$

$$V_{(out)} = R_{load}(I_T - N_1 i_5 + i_5)$$

$$V_{(out)} = V_{(out)} N_1 - V_{(p)} N_1$$

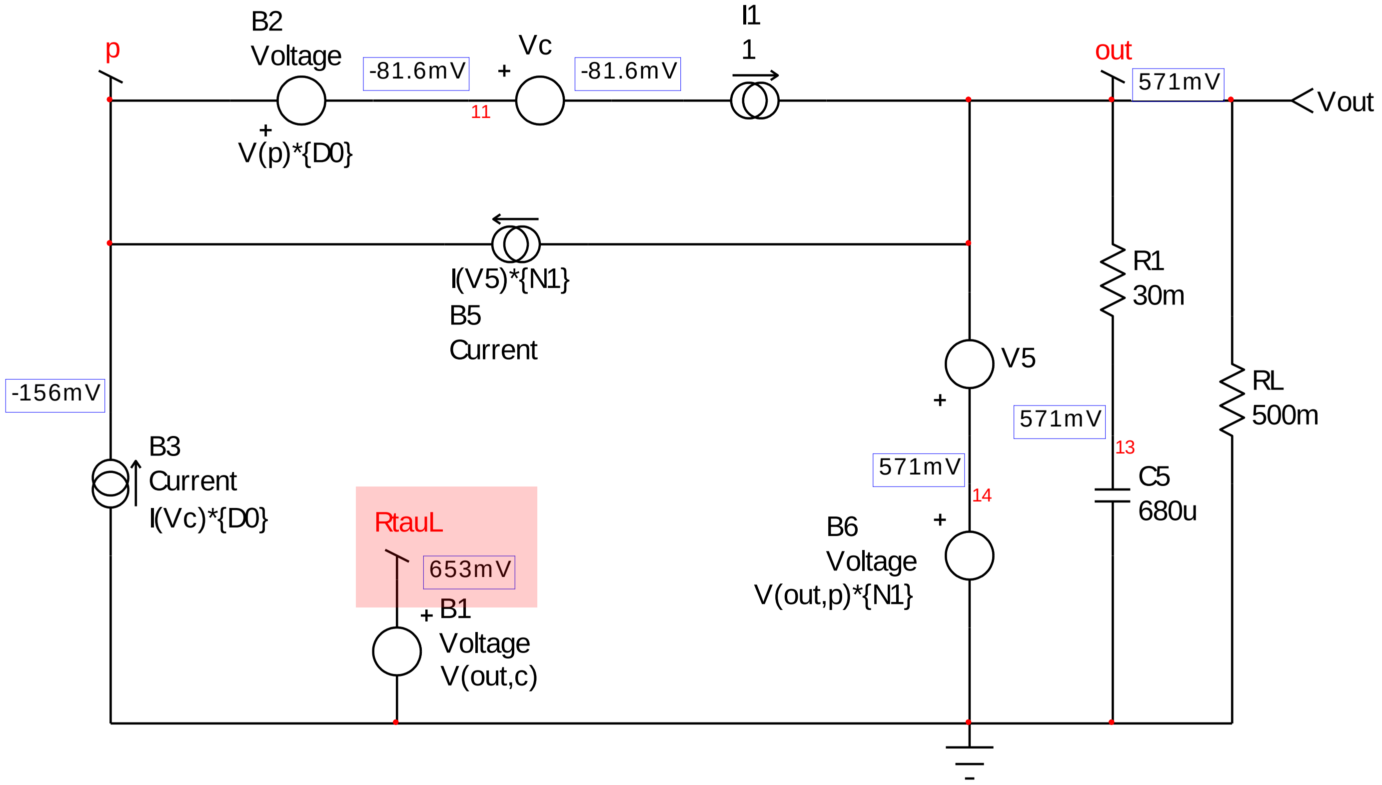
$$\tau_1 = \frac{L_f N_1^2}{R_{load}(D_0 N_1 - D_0 + 1)^2}$$

Determination of the time constant involving inductance L_f. In this mode, C_{out} is set into its dc state while the test generator I_T is applied across L_f's connecting terminals.

Sanity check with SPICE making sure the derivation is:

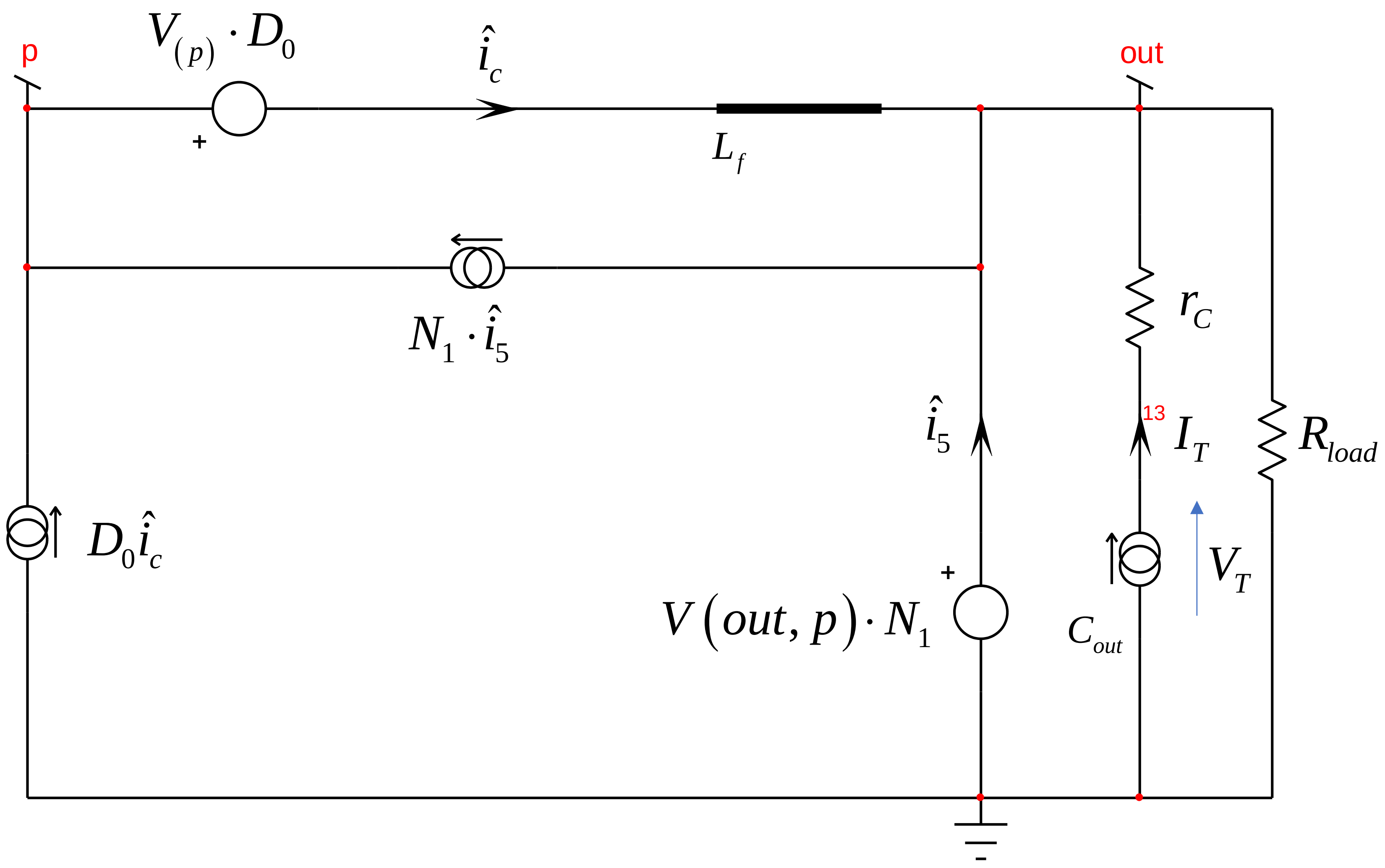
parameters

L1=100u
Nfly=550m
Npush=700m
Lf=L1*Npush^2
N1=(1/Npush)*Nfly
D0=0.47619

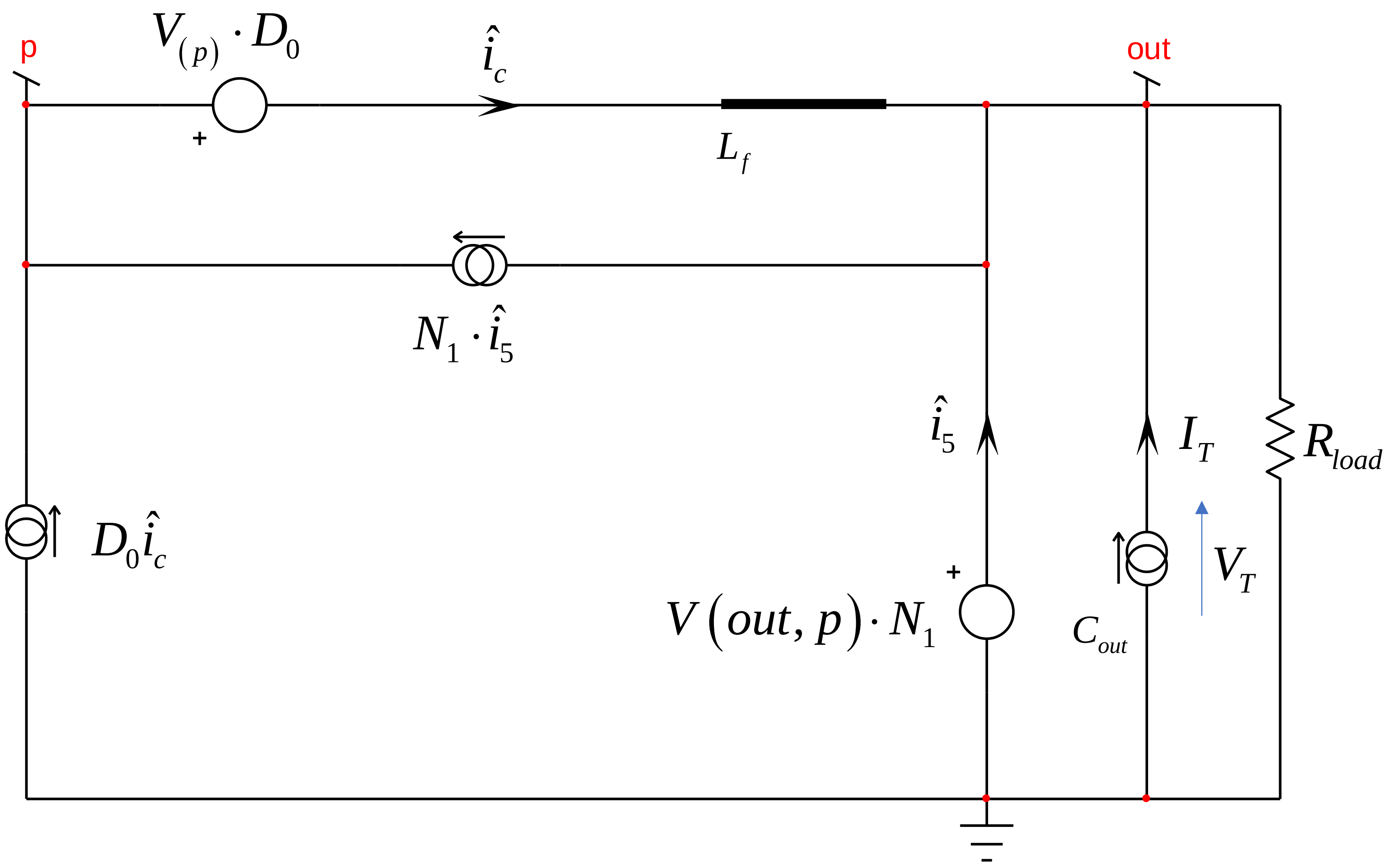


$$\frac{R_{load}\cdot\left(D_1\cdot N_1 - D_1 + 1\right)^2}{{N_1}^2} = 0.65306\,\Omega$$

$$\tau_1 := \frac{L_f\cdot {N_1}^2}{R_{load}\cdot\left(D_1\cdot N_1 - D_1 + 1\right)^2} = 75.03123\,\mu s$$



Determination of the time constant involving capacitor C_{out}. In this mode, L_f is set into its dc state while the test generator I_T is applied across C_{out}'s connecting terminals.



$$V_T = V_{(out)}$$

$$V_{(out)} = V_{(out)} N_1 - V_{(p)} N_1$$

$$V_{(p)} = -\frac{V_{(out)} - N_1 V_{(out)}}{N_1}$$

$$V_{(p)} - V_{(p)} D_0 = V_{(out)}$$

$$V_{(p)} = \frac{V_{(out)}}{1 - D_0}$$

$$\frac{V_{(out)}}{1 - D_0} = -\frac{V_{(out)} - N_1 V_{(out)}}{N_1}$$

$$\rightarrow V_{(out)} = V_T = 0 \text{ V}$$

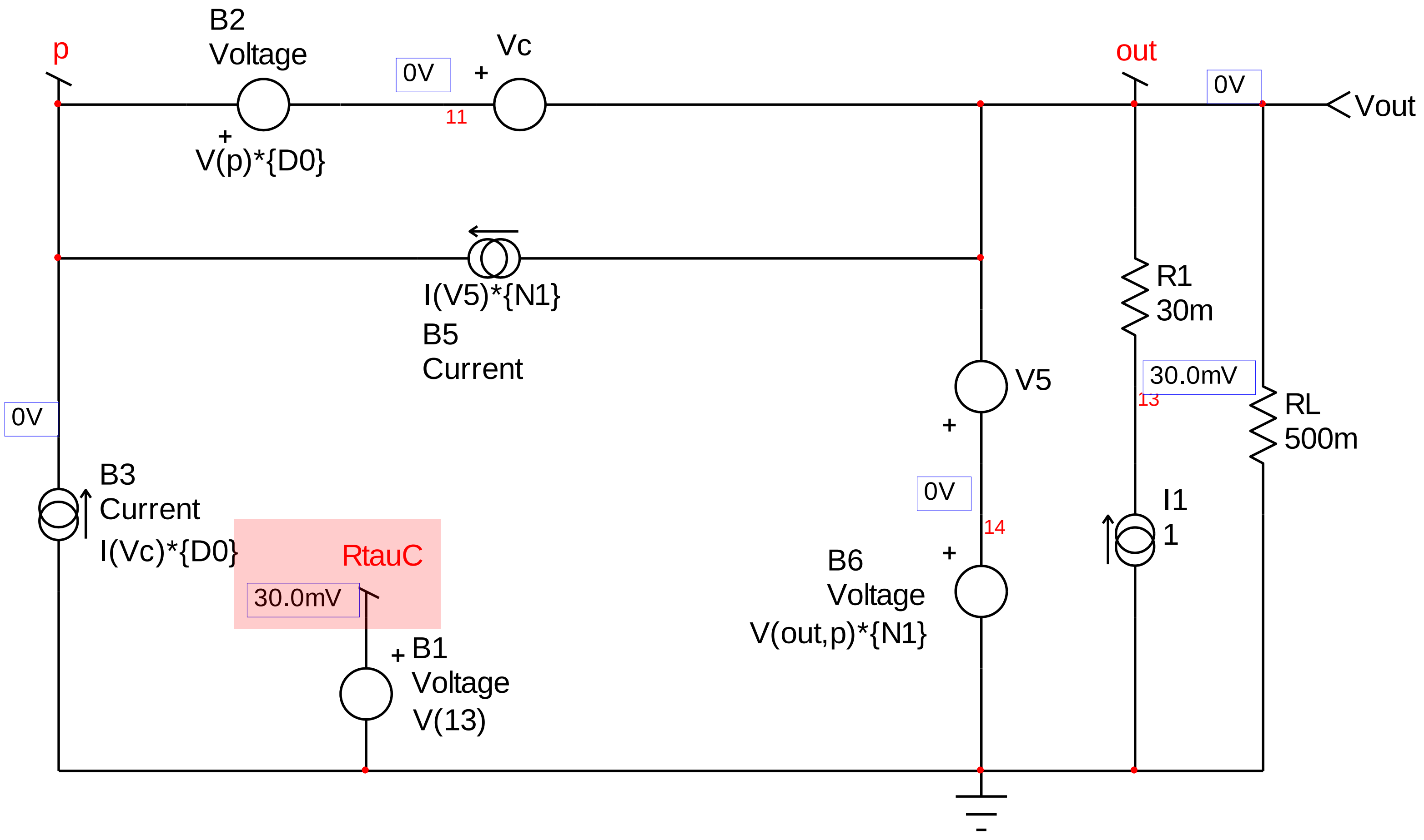
$$\tau_2 = r_C C_{out}$$

The final resistance will be r_C in series with some terms. We can remove r_C, determine the intermediate resistance in this mode and then add r_C to form the final time constant. It appears that the intermediate resistance is 0 ohm.

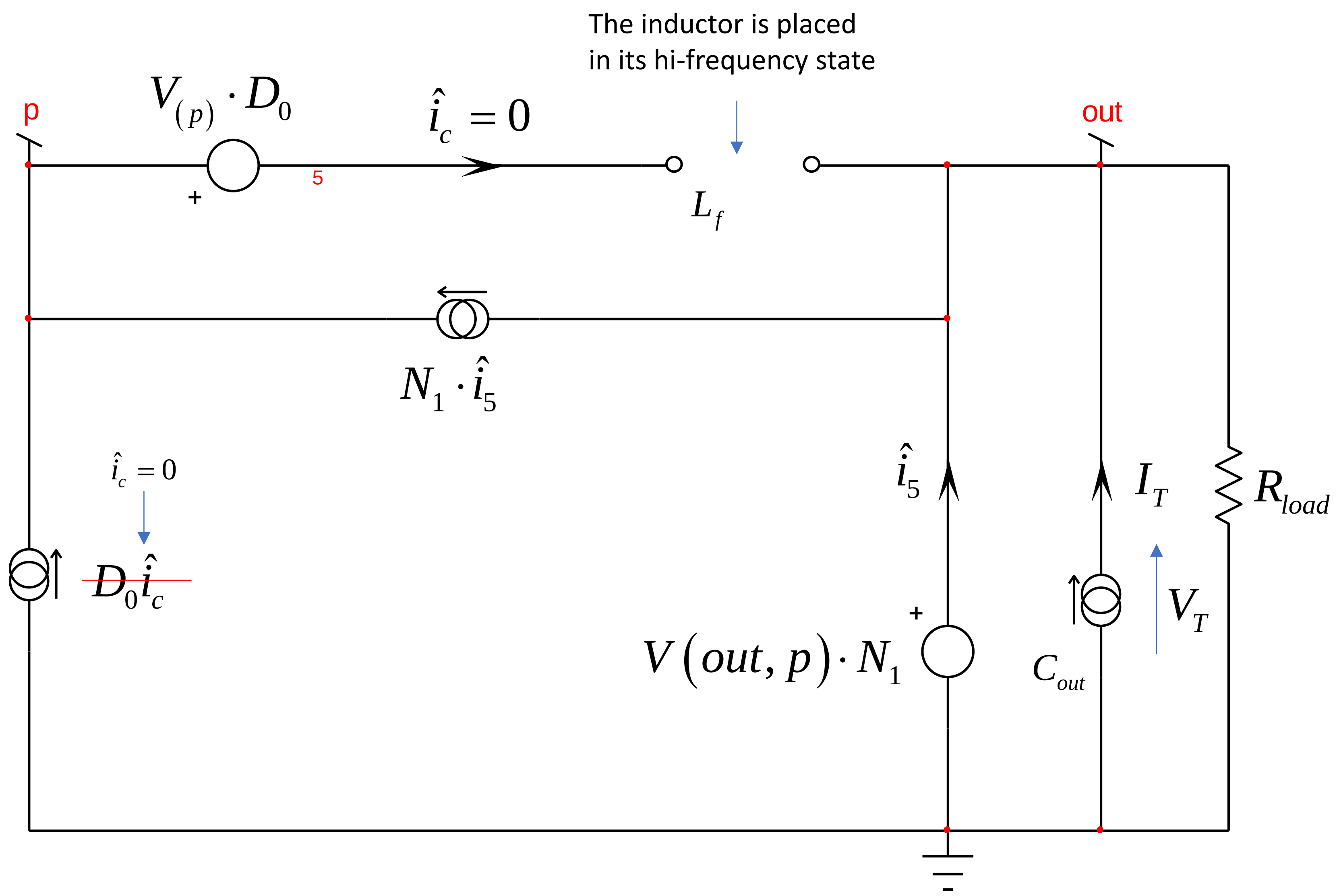
Verification of the resistance value with a bias point:

parameters

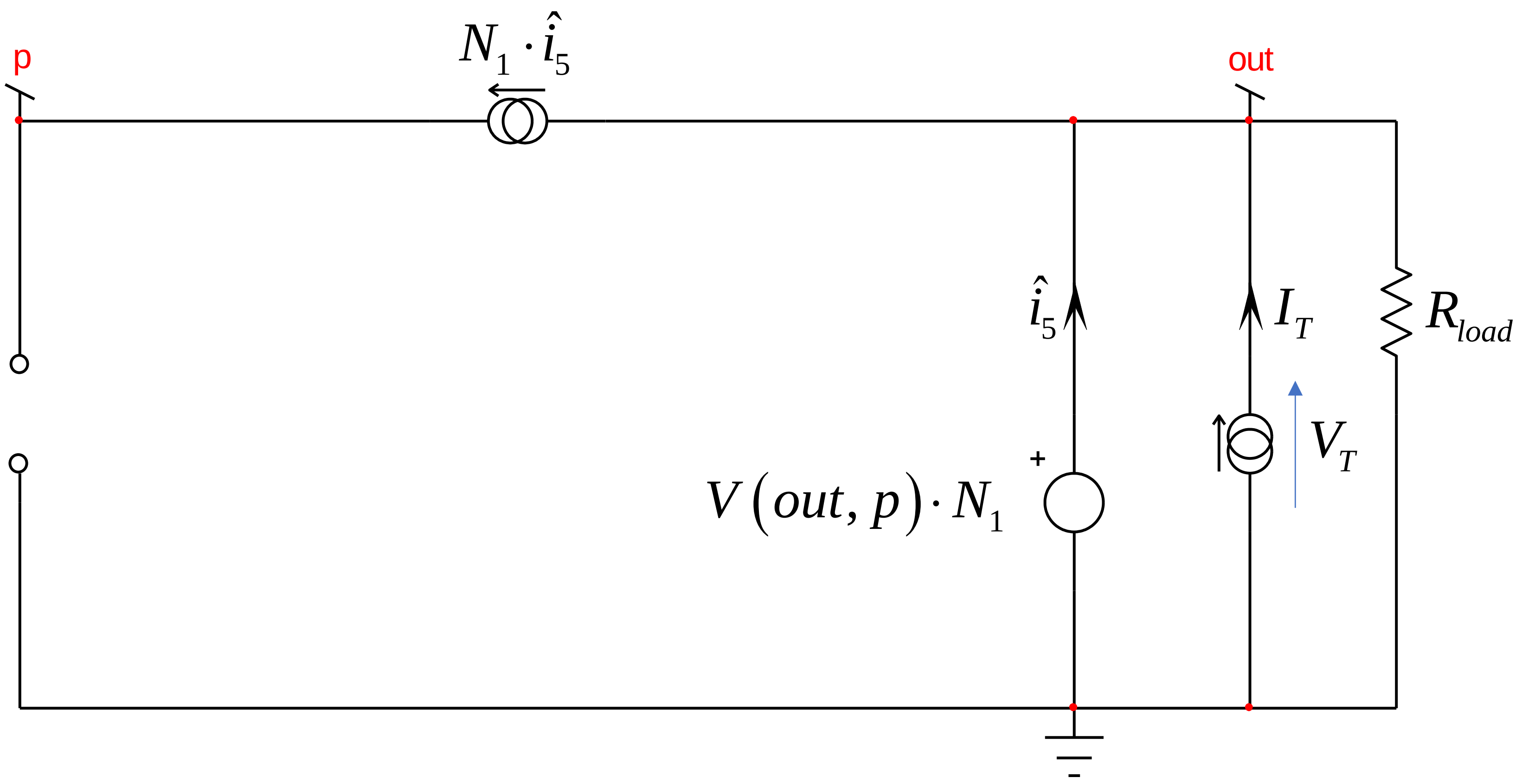
L1=100u
Nfly=550m
Npush=700m
Lf=L1*Npush^2
N1=(1/Npush)*Nfly
D0=0.47619



$$b_1 = \tau_1 + \tau_2 = \frac{L_f N_1^{\,2}}{R_{load}\left(D_0 N_1 - D_0 + 1\right)^2} + r_C C_{out}$$



Now that we have determined b_1 by summing all time constants, we can determine b_2 by identifying the time constant when the inductor is placed in its high-frequency state. Again, r_C is temporarily removed and will be added to this intermediate result.



There is no current going to the p node and there is no current flowing out of the voltage source:

$$V_{(out)}N_1 - V_{(p)}N_1 = V_{(out)}$$

$$V_{(p)} = N_1 i_5 R_{INF}$$

$$V_{(p)} = N_1 i_5 R_{INF}$$

$$i_5 = \frac{V_{(p)}}{N_1 R_{INF}} \rightarrow i_5 = 0$$

$$i_5 + I_T = \frac{V_T}{R_{load}} - N_1 i_5$$

$$\frac{V_T}{I_T} = R_{load}$$

$$\tau_2^1 = C_{out}\left(r_C + R_{load}\right)$$

With this last time constant, we can now express the term b_2 and the denominator $D(s)$:

$$b_2 = \tau_1 \tau_2^1 = \frac{L_f N_1^2}{R_{load}\left(D_0 N_1 - D_0 + 1\right)^2} C_{out}\left(r_C + R_{load}\right)$$

$$D(s) = 1 + b_1 s + b_2 s^2 = 1 + s\left(\tau_1 + \tau_2\right) + s^2 \tau_1 \tau_2^1$$

$$D(s) = 1 + s\left(\frac{L_f N_1^2}{R_{load}\left(D_0 N_1 - D_0 + 1\right)^2} + r_C C_{out}\right) + s^2 \frac{L_f N_1^2}{R_{load}\left(D_0 N_1 - D_0 + 1\right)^2} C_{out}\left(r_C + R_{load}\right)$$

$$D(s) = 1 + s\left(\frac{L_f N_1^{\,2}}{R_{load}\left(D_0 N_1 - D_0 + 1\right)^2} + r_C C_{out}\right) + s^2 \frac{L_f N_1^{\,2}}{R_{load}\left(D_0 N_1 - D_0 + 1\right)^2} C_{out}\left(r_C + R_{load}\right)$$

$$D(s) = 1 + \frac{s}{\omega_0 Q} + \left(\frac{s}{\omega_0}\right)^2 \rightarrow \omega_0 = \frac{1}{\sqrt{b_2}} \quad Q = \frac{\sqrt{b_2}}{b_1}$$

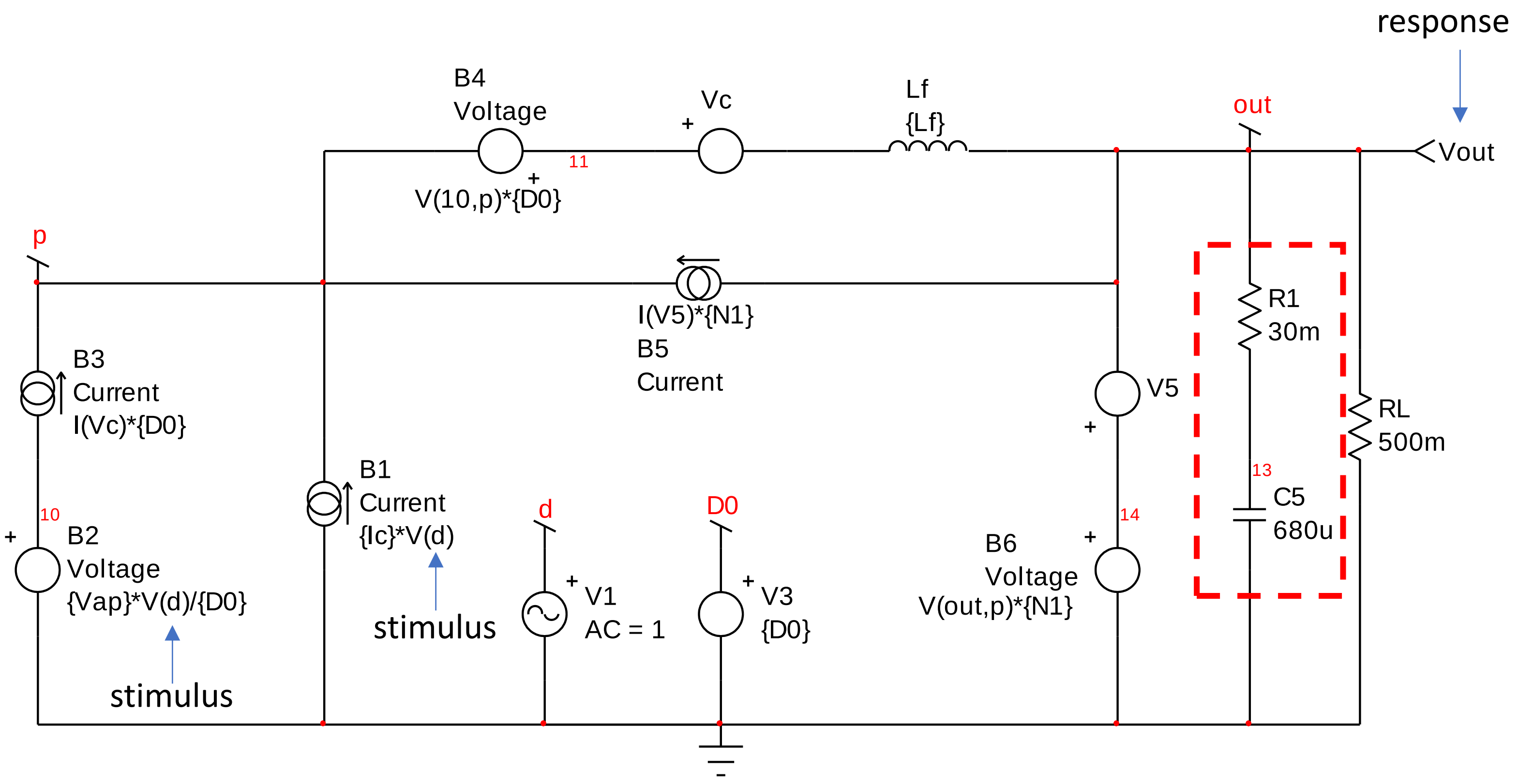
$$\omega_0 = \frac{1}{\sqrt{\frac{L_f N_1^{\,2}}{R_{load}\left(D_0 N_1 - D_0 + 1\right)^2} C_{out}\left(r_C + R_{load}\right)}} \qquad Q = \frac{\sqrt{\frac{L_f N_1^{\,2}}{R_{load}\left(D_0 N_1 - D_0 + 1\right)^2} C_{out}\left(r_C + R_{load}\right)}}{\frac{L_f N_1^{\,2}}{R_{load}\left(D_0 N_1 - D_0 + 1\right)^2} + r_C C_{out}}$$

If we neglect the ESR contribution, $r_C << R_{load}$:

$$\omega_0 \approx \frac{\left(N_1 - 1\right) D_0 + 1}{N_1} \frac{1}{\sqrt{L_f C_{out}}} \qquad Q \approx \frac{R_{load}\left(N_1 - 1\right) D_0 + 1}{N_1} \sqrt{\frac{C_{out}}{L_f}}$$

parameters

Vin=15
L1=100u
Nfly=700m
Npush=700m
Lf=L1*Npush^2
Vg=Vin*Npush
N1=(1/Npush)*Nfly
D0=0.48
Ic=10.08
Vap=10.5

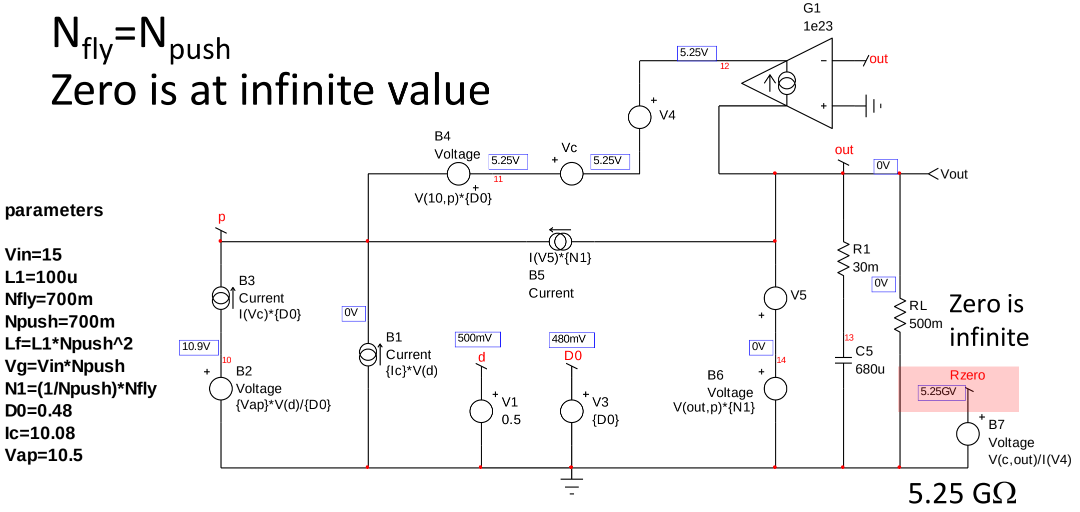


The determination of the zeroes requires a null double injection or NDI. The generalized approach can also be used if the NDI is complicated. However, by inspection, we can already identify the zero brought by the ESR and the output capacitor:

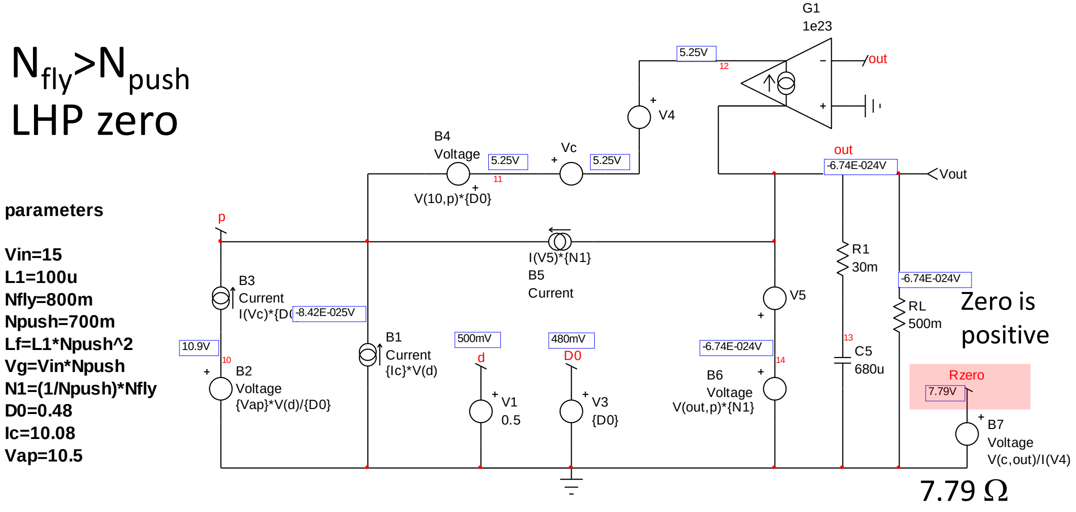
$$\omega_{z_1} = \frac{1}{r_C C_{out}}$$

Before we proceed, we can check the presence of a second zero linked to the inductance. We can simulate the NDI with 3 different configurations: $N_{fly}=N_{push}$, $N_{fly}<N_{push}$ and $N_{fly}>N_{push}$ and see if there is a zero:

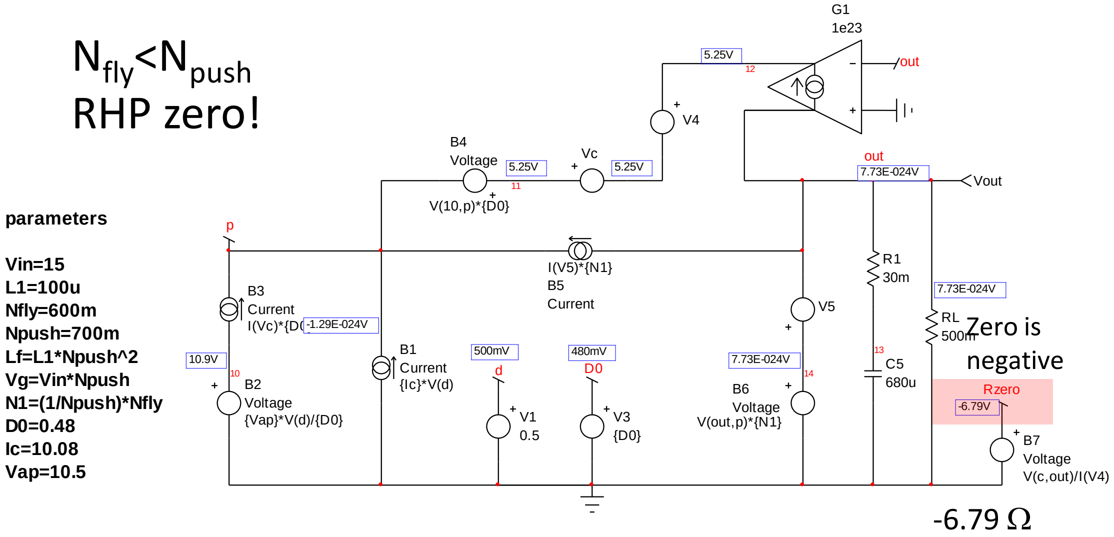
$N_{fly}=N_{push}$
Zero is at infinite value



$N_{fly}>N_{push}$
LHP zero

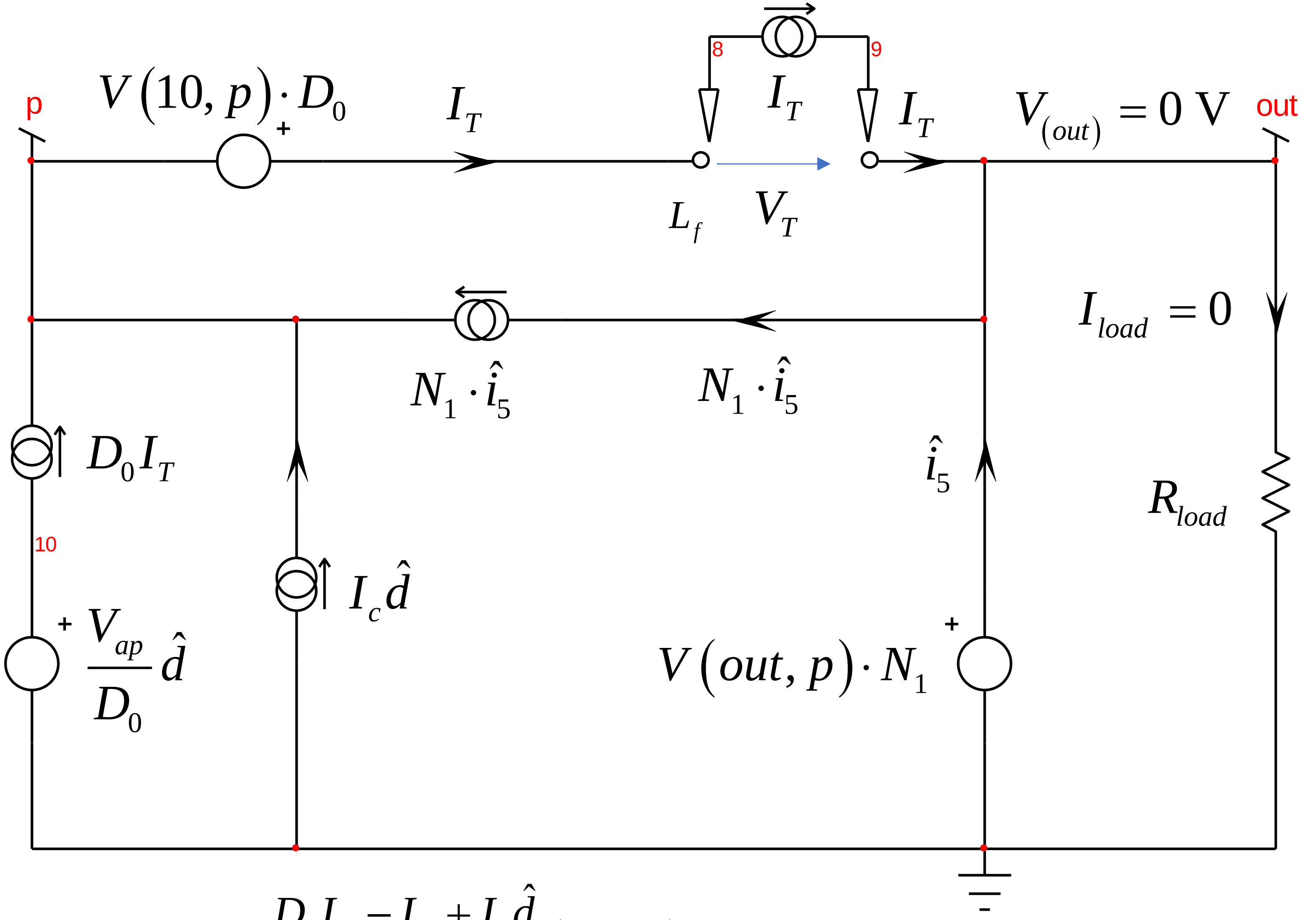


$N_{fly}<N_{push}$
RHP zero!



The position of the second zero depends on the transformers turns ratios:

- $N_{fly}=N_{push}$ there is no zero (pushed to infinity)
- $N_{fly}<N_{push}$ there is one zero in the right half plane
- $N_{fly}>N_{push}$ there is one zero in the left half plane



$$I_T = i_5\left(N_1 - 1\right)$$

$$V_{(p)} + V_{(10)}D_0 - V_{(p)}D_0 + V_T = 0$$

$$V_{(out)}N_1 - V_{(p)}N_1 = 0$$

0 V

$$\Rightarrow V_{(p)} = 0$$

$$V_T = -V_{(10)}D_0$$

$$V_T = -\frac{V_{ap}}{D_0}D_0\hat{d} = -V_{ap}\hat{d}$$

$$I_T = D_0 I_T + I_c\hat{d} + N_1 i_5$$

$$\Rightarrow i_5 = -\frac{D_0 I_T - I_T + I_c\hat{d}}{N_1}$$

$$I_T = -\frac{D_0 I_T - I_T + I_c\hat{d}}{N_1}\left(N_1 - 1\right)$$

$$\Rightarrow I_T = \frac{I_c\hat{d} - I_c N_1\hat{d}}{D_0 N_1 - D_0 + 1}$$

$$\Rightarrow \frac{V_T}{I_T} = -\frac{V_{ap}\hat{d}}{\dfrac{I_c\hat{d} - I_c N_1\hat{d}}{D_0 N_1 - D_0 + 1}} = \frac{V_{ap}\left[D_0\left(N_1 - 1\right) + 1\right]}{I_c\left(N_1 - 1\right)}$$

$N_{fly}<N_{push}$ $N_{fly}>N_{push}$ $N_{fly}=N_{push}$

$$\frac{V_{ap}\cdot\left[\left(N_1-1\right)\cdot D_1+1\right]}{I_c\cdot\left(N_1-1\right)} = -6.79167\,\Omega$$

$$\frac{V_{ap}\cdot\left[\left(N_1-1\right)\cdot D_1+1\right]}{I_c\cdot\left(N_1-1\right)} = 7.79167\,\Omega$$

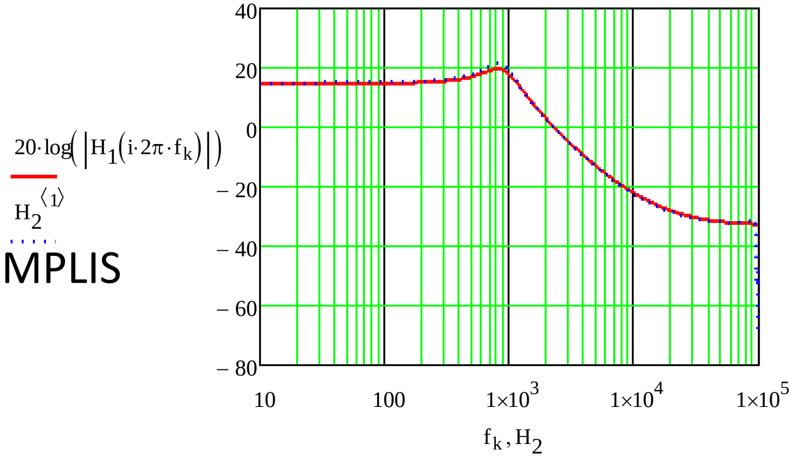
$$\frac{V_{ap}\cdot\left[\left(N_1-1\right)\cdot D_1+1\right]}{I_c\cdot\left(N_1-1\right)} = -7.29167\times 10^{8}\,\Omega$$

Final transfer function of the Weinberg converter operated in voltage-mode control:

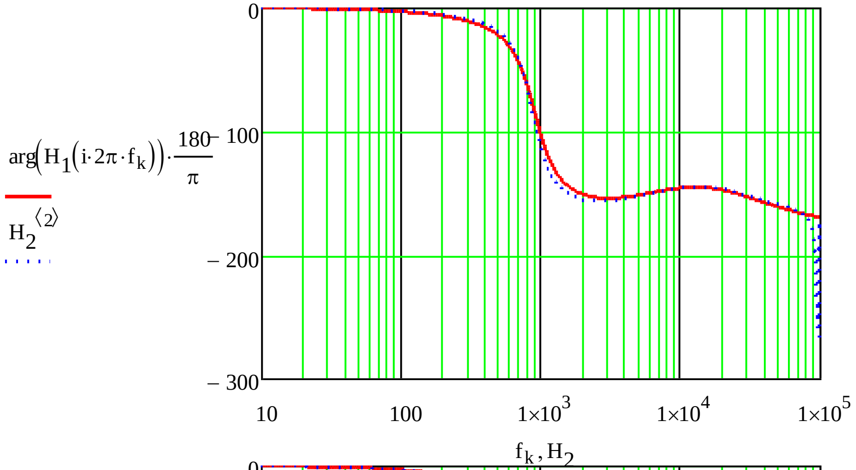
$$H(s) = H_0 \frac{\left(1+\frac{s}{\omega_{z_1}}\right)\left(1+\frac{s}{\omega_{z_2}}\right)}{1+\frac{s}{\omega_0 Q}+\left(\frac{s}{\omega_0}\right)^2} \qquad H_0 = \frac{1}{V_p}\frac{N_{fly}N_{push}{}^2 V_{in}}{\left[\left(N_{fly}-N_{push}\right)D+N_{push}\right]^2}$$

$$\omega_{z_1} = \frac{1}{r_C C_{out}} \qquad \omega_{z_2} = \frac{V_{ap}\left[\left(N_1-1\right)D_0+1\right]}{I_c L_f\left(N_1-1\right)}$$

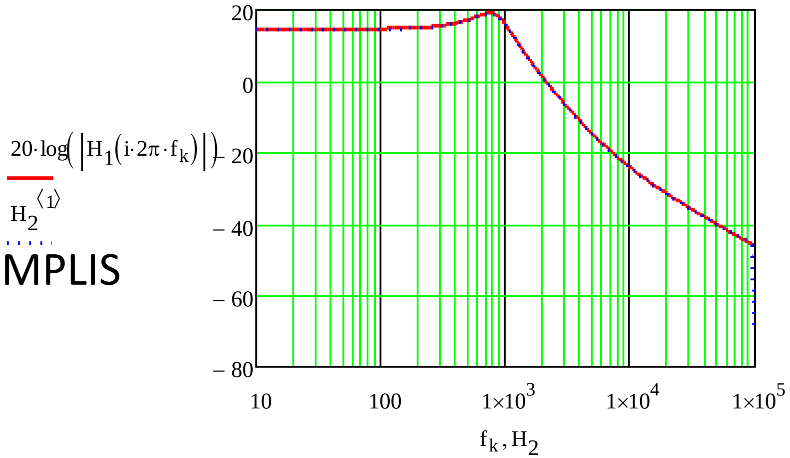
$$\omega_0 = \frac{1}{\sqrt{\frac{L_f N_1^{\,2}}{R_{load}\left(D_0 N_1 - D_0 + 1\right)^2} C_{out}\left(r_C + R_{load}\right)}} \qquad Q = \frac{\sqrt{\frac{L_f N_1^{\,2}}{R_{load}\left(D_0 N_1 - D_0 + 1\right)^2} C_{out}\left(r_C + R_{load}\right)}}{\frac{L_f N_1^{\,2}}{R_{load}\left(D_0 N_1 - D_0 + 1\right)^2} + r_C C_{out}}$$



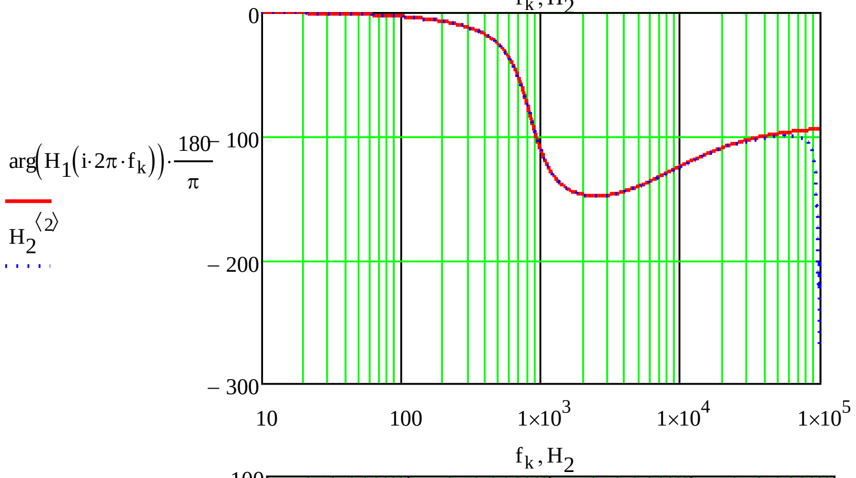
SIMPLIS



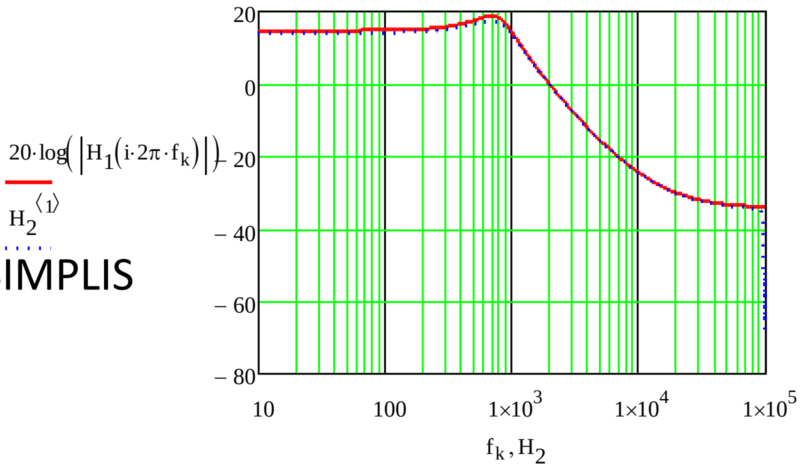
N_{fly} = 0.6
N_{push} = 0.7
RHPZ



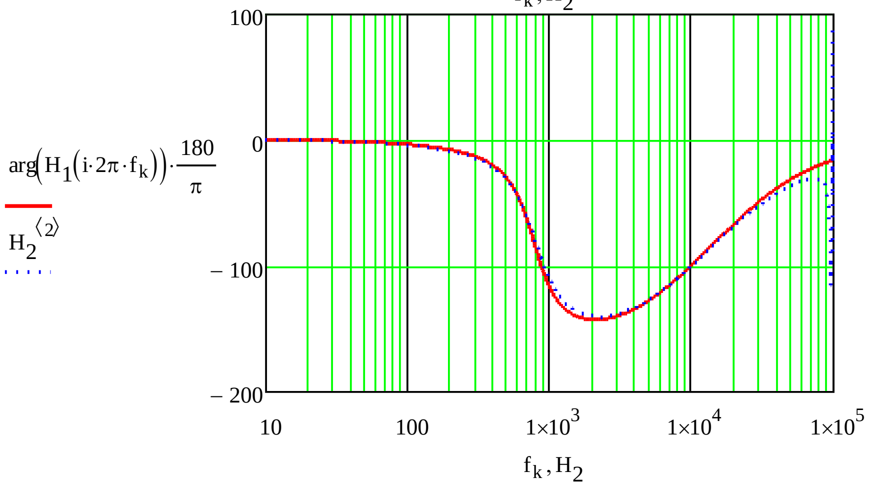
SIMPLIS



N_{fly} = 0.7
N_{push} = 0.7
Zero at infinity

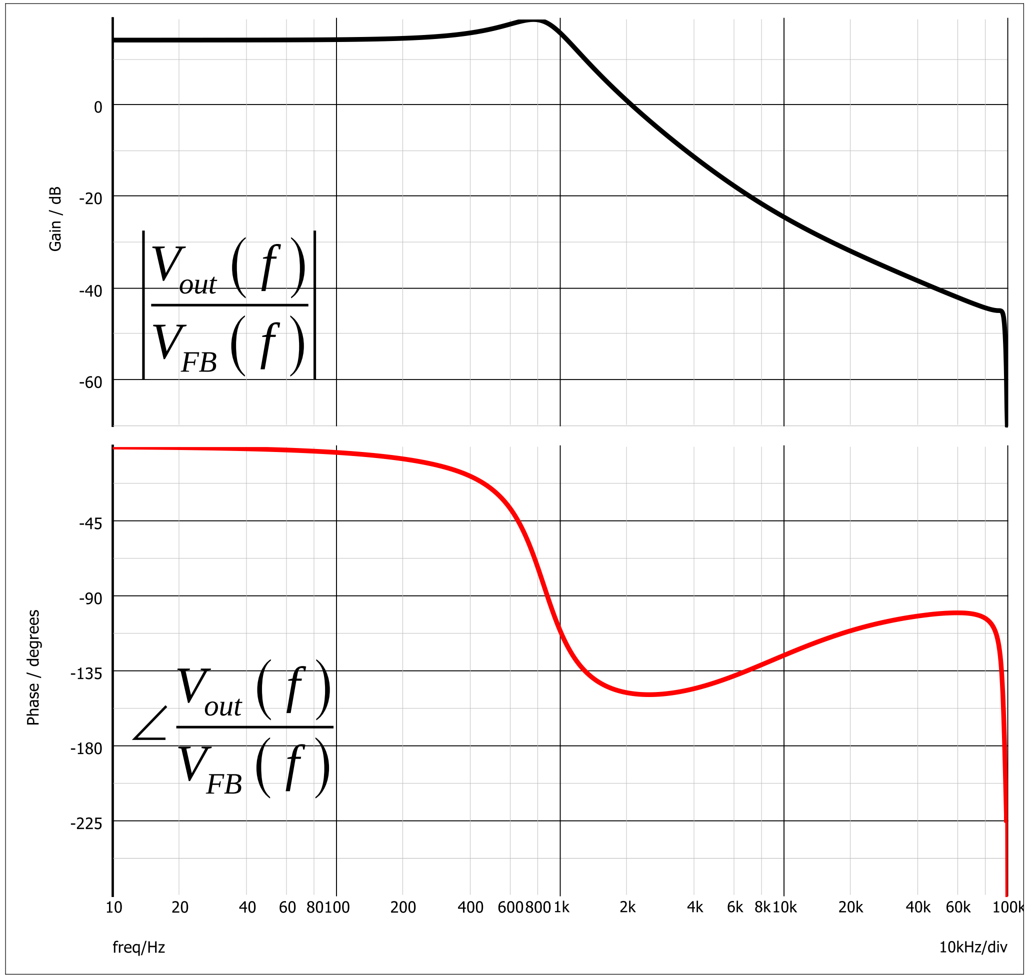


SIMPLIS

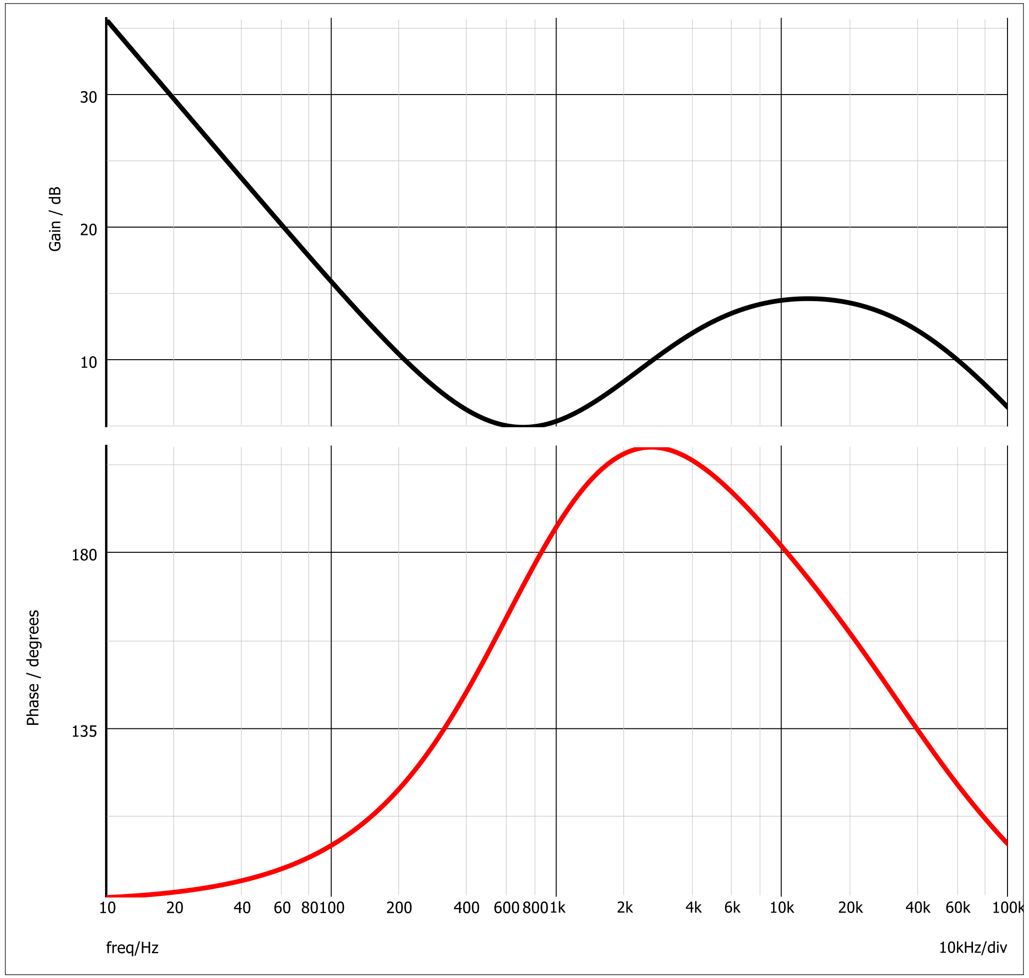


N_{fly} = 0.8
N_{push} = 0.7
LHP zero

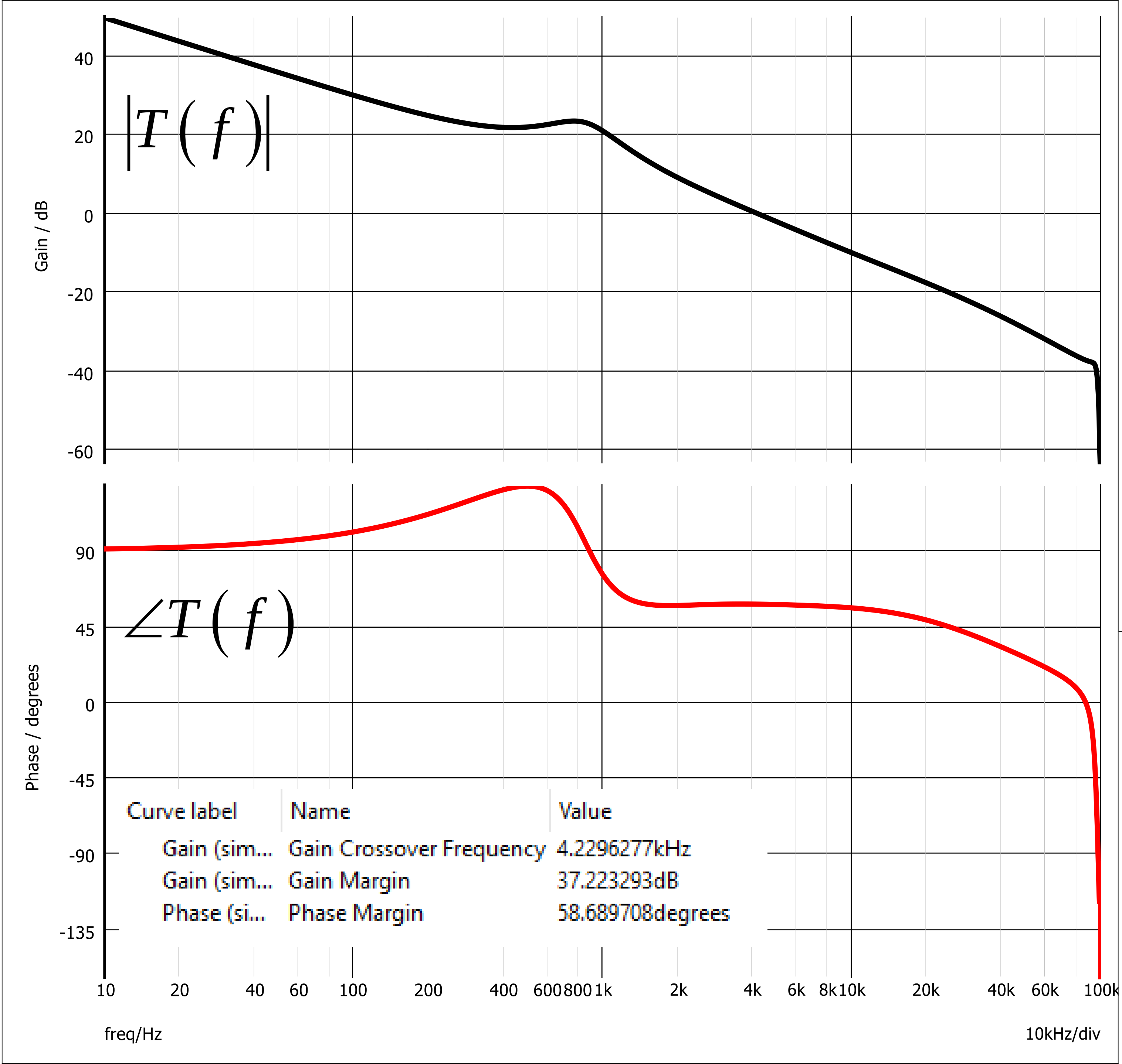
We can stabilize the converter with the automated macro and a type 3 compensator:

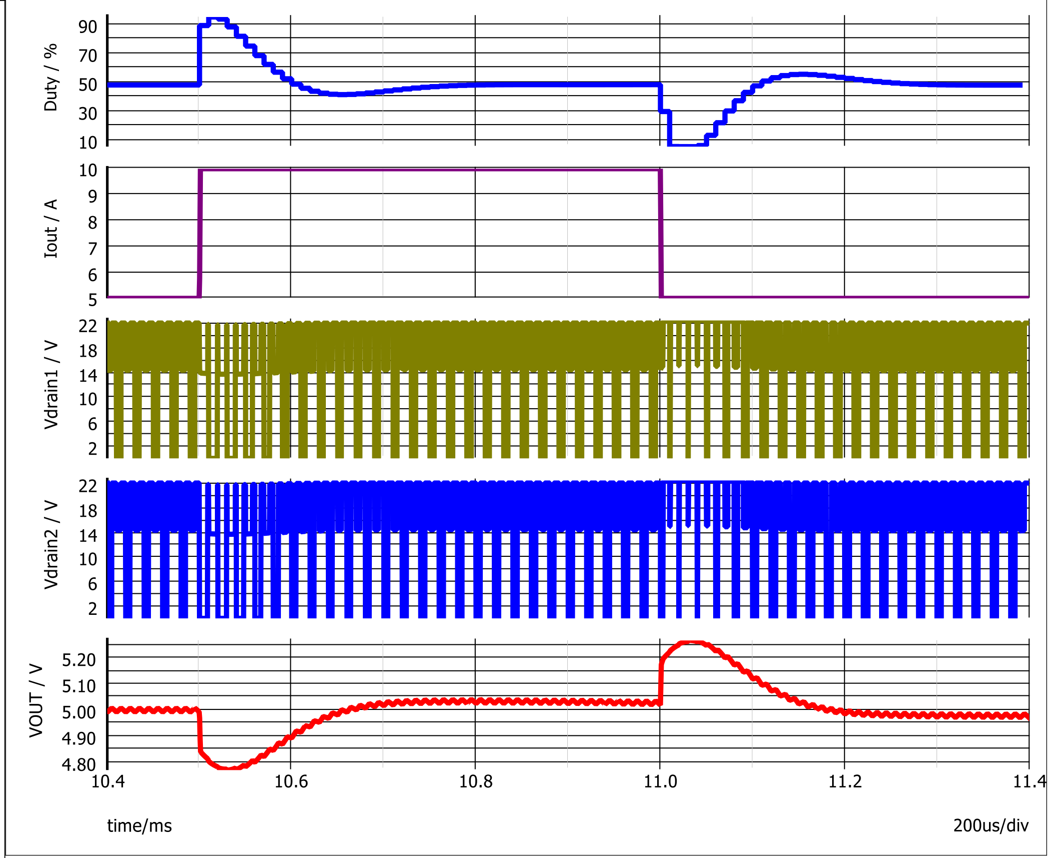


Control-to-output transfer function. Extract magnitude and phase at a 4-kHz crossover frequency.



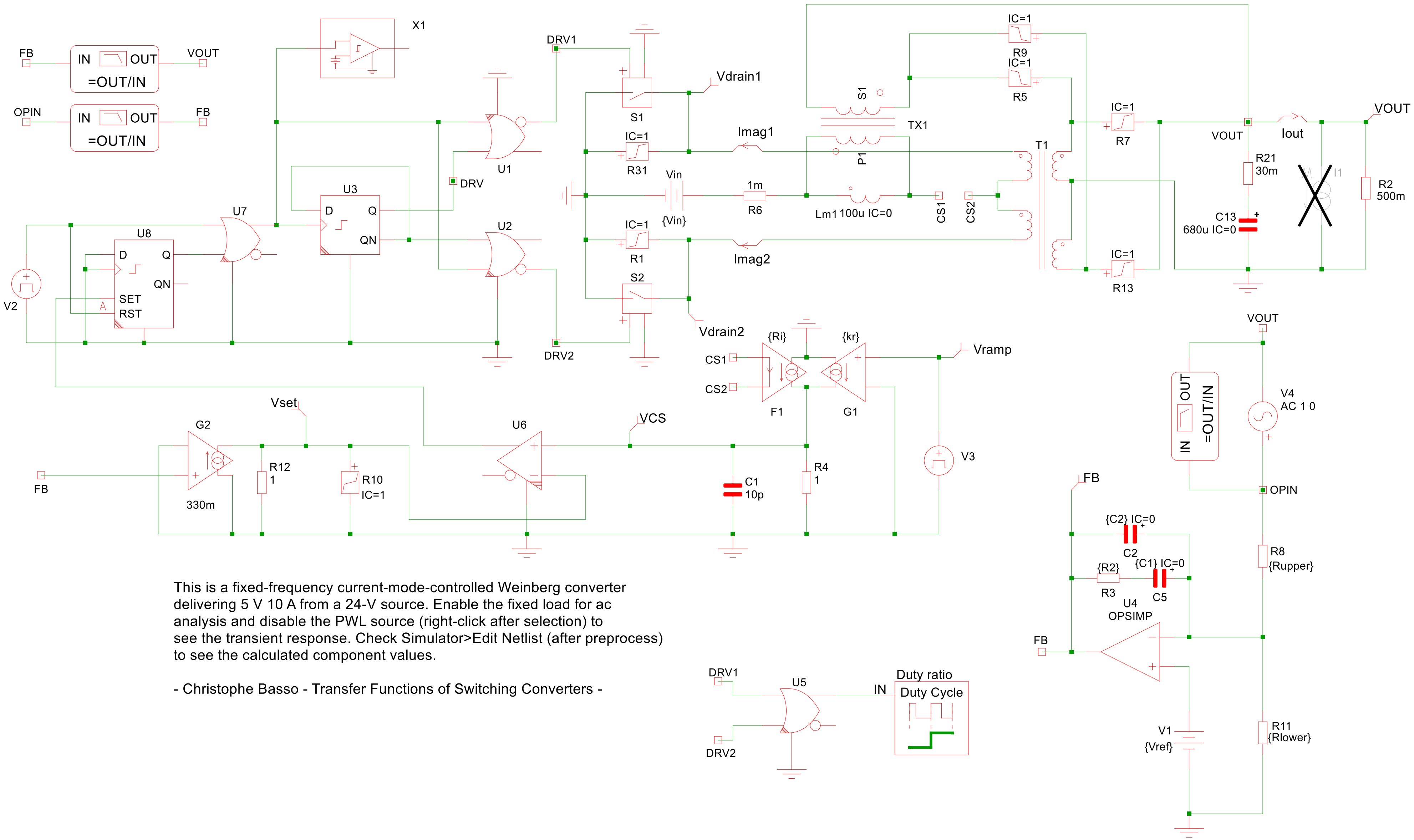
The type 3 compensator places zeroes at 800 and 600 Hz then adjusts the pole to boost the phase for a 60° phase margin.





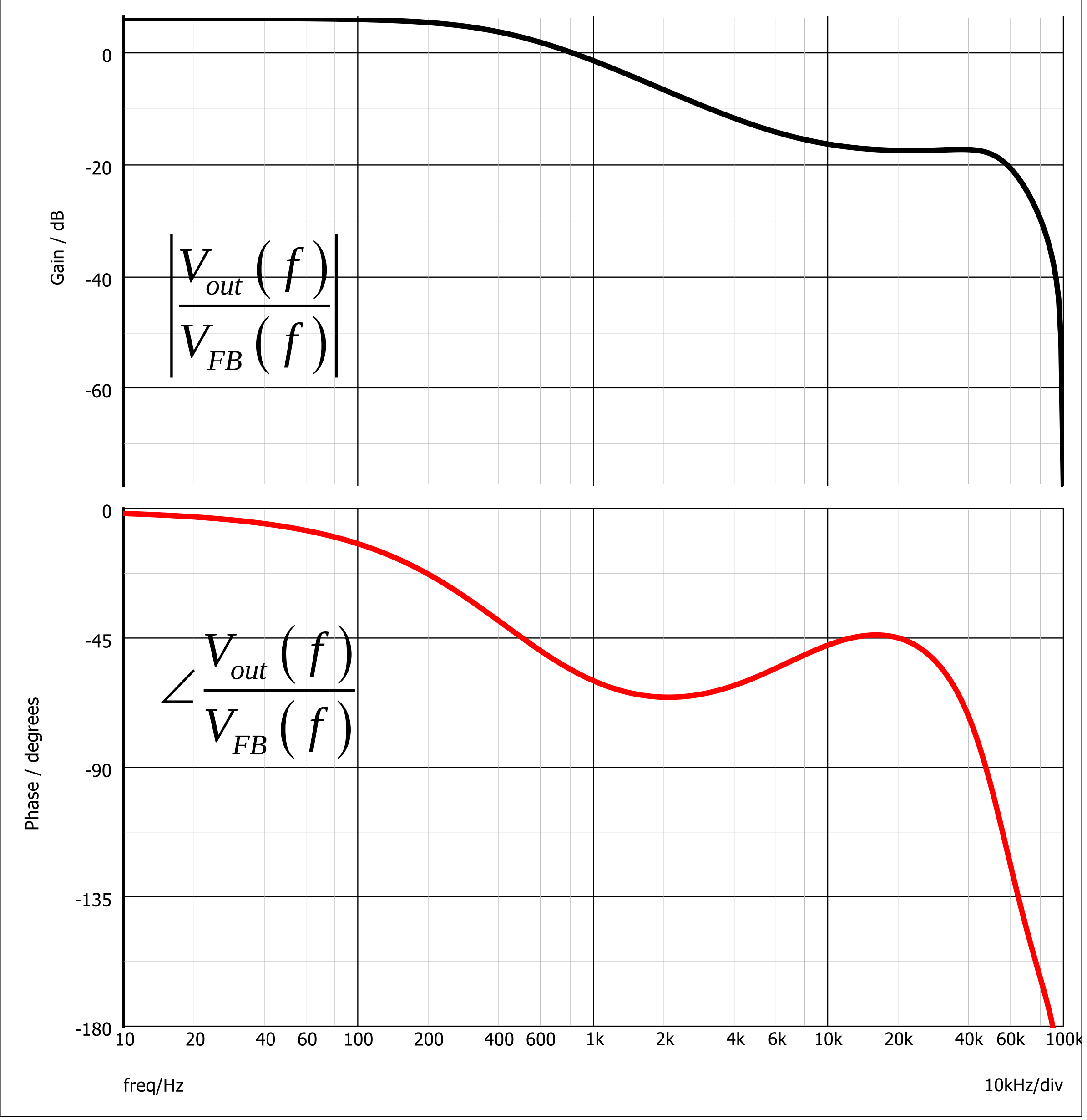
This is the transient response for a step load of 5 to 10 A in 1 µs. In lack of RHP zero for the same turns ratio between the flyback and push-pull transformers, it becomes possible to extend the crossover frequency in boost mode. The SIMPLIS Weinberg converter is included in my 130+ ready-made templates available here.

I also built a current-mode version with similar characteristics as in VM. The response is of first order this time in the low-frequency area:

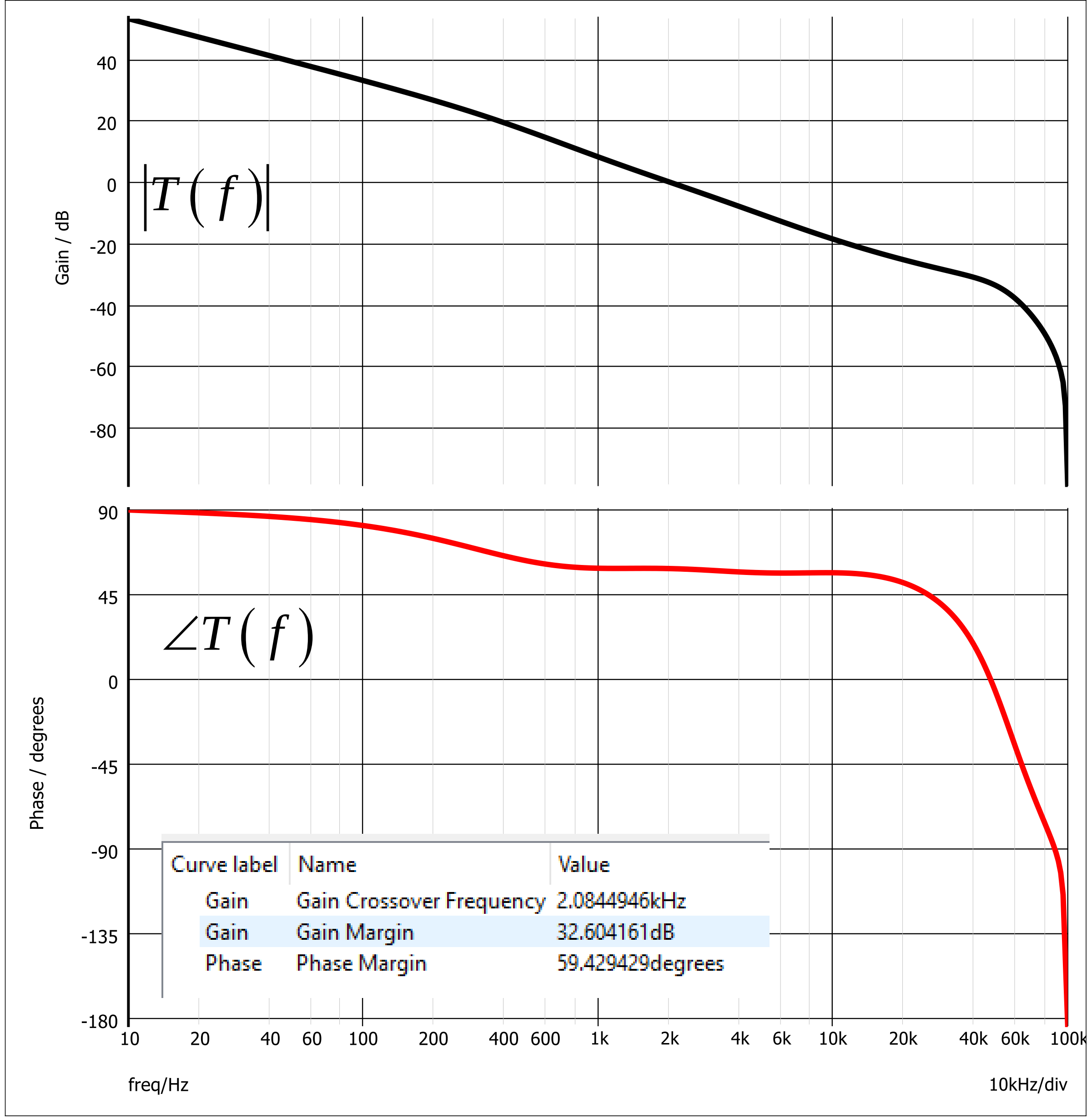


Slope compensation

```
.VAR Sn={((Vin-Vout/Npush)/Lm)*Ri}
.VAR Sramp={1/Ts}
.VAR Q=1 ; select Q
.VAR mc={((0.318/Q)+0.5)/(1-D)}
.VAR Se={(mc-1)*Sn}
.VAR kr={Se/Sramp}
*
```



Control-to-output transfer function in CM. Extract magnitude and phase at a 2-kHz crossover frequency.



The type 2 compensator places 1 zero and one pole to boost the phase for a 60° phase margin at 2 kHz. This loop gain confirms our goal is obtained.

[Transfer functions of switching converters]

If you want to learn how to derive transfer functions of switching converters, my 2021 book on the subject starts smoothly with an introduction to small-signal modeling and then goes in all possible details to unveil many transfer functions from the basic switching cells to the more complicated higher-order isolated structures. The table of content is [here].