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Over Power Phenomenon in Forward Converters

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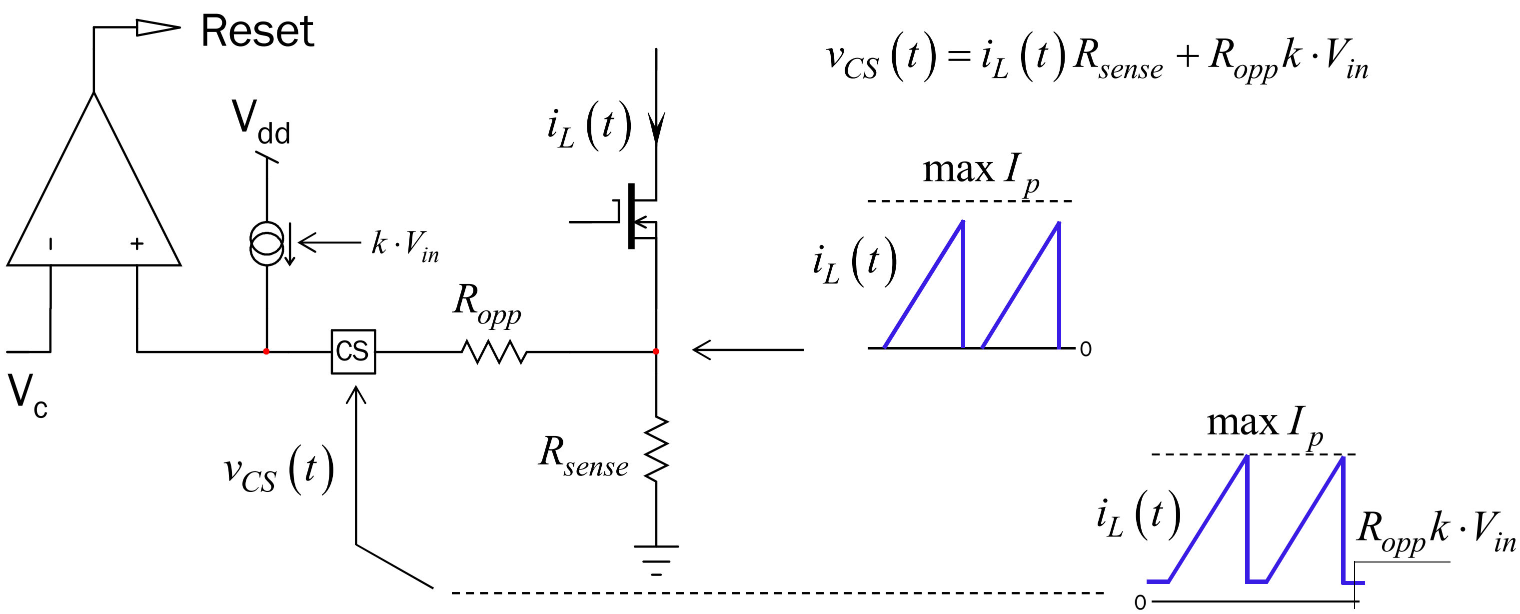
IEEE- Senior Member

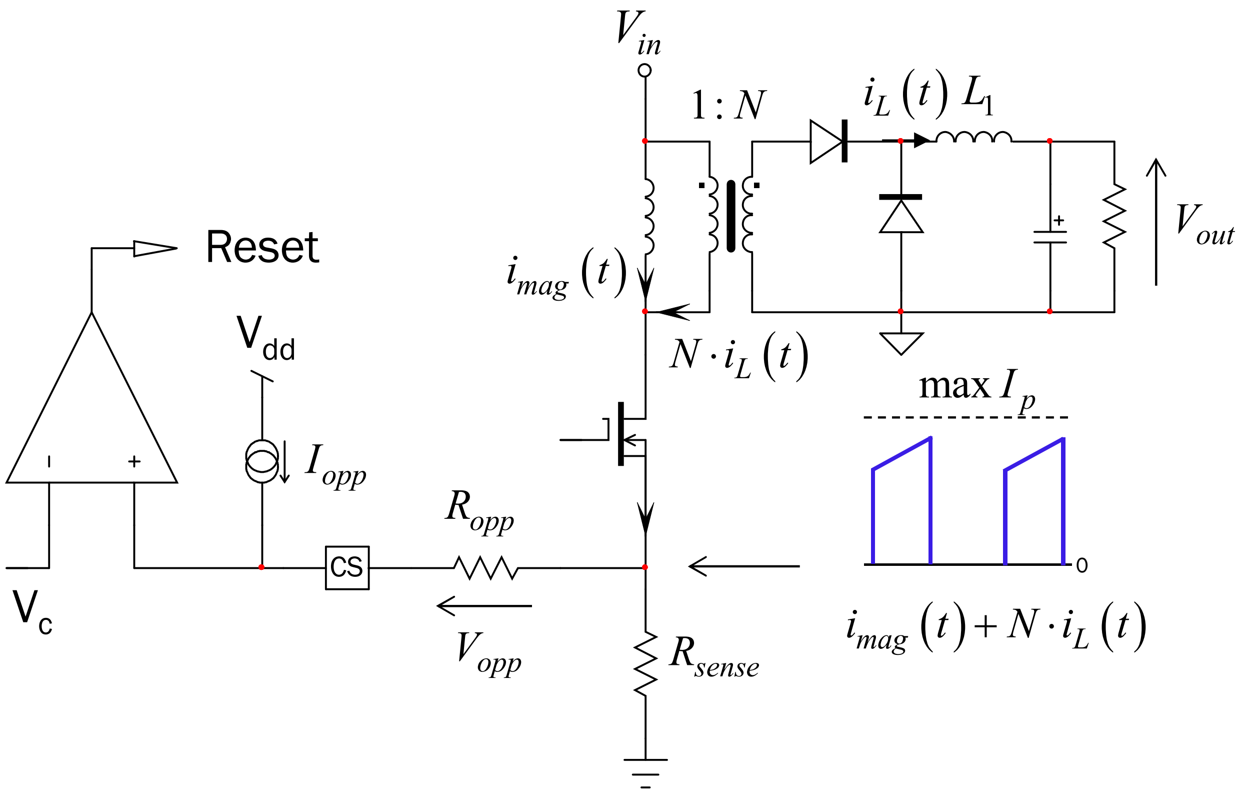
The Classical Way with a Flyback

- ❑ Flyback converters suffer from the over power phenomenon
- ❖ The transmitted power at high line is greater than that at low line
- ❖ A known way to overcome this issue is to offset the current sense
- ❖ The peak current is reduced and it helps in DCM and CCM



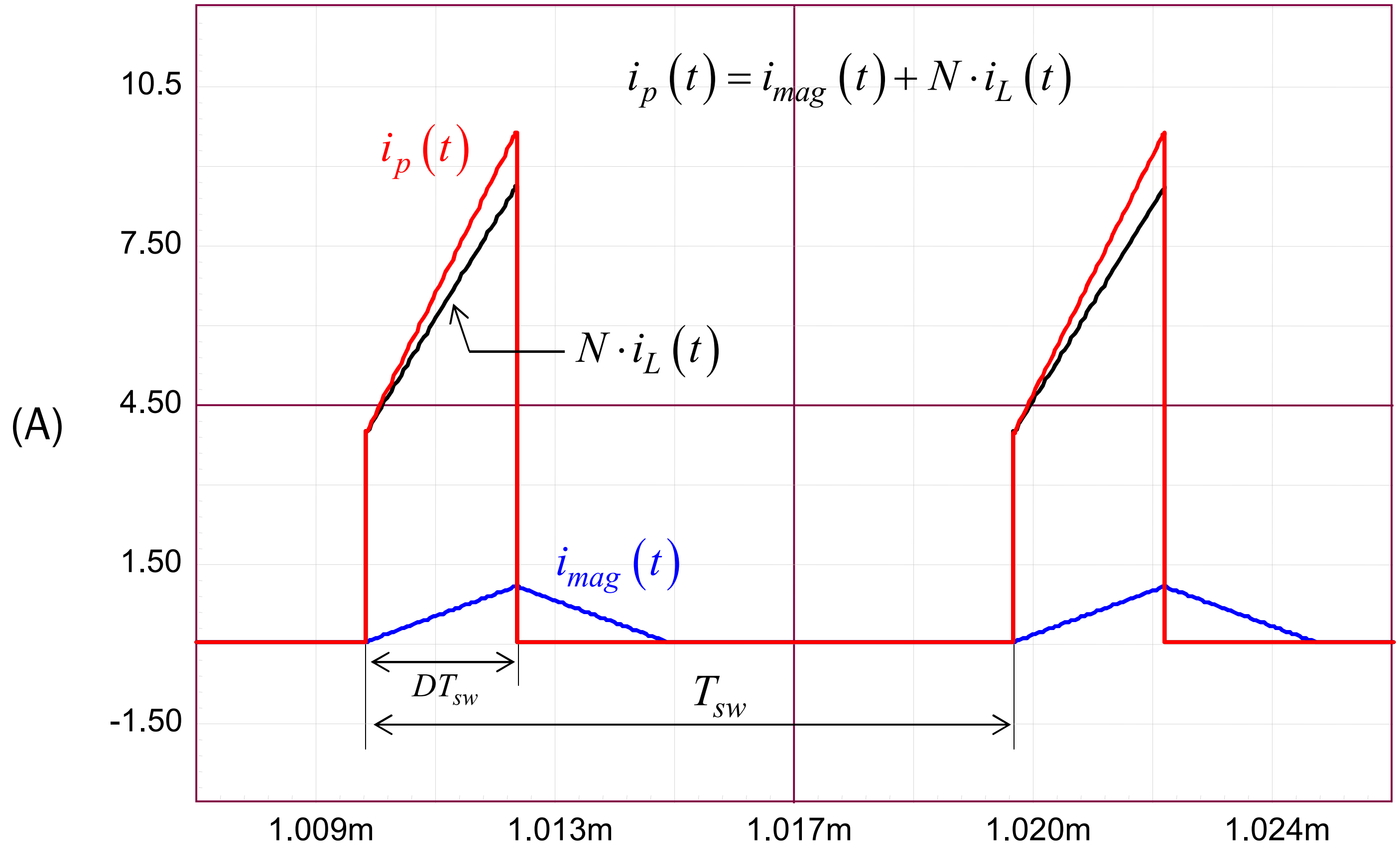
The Forward Converter

- ❑ Forward converters may behave differently
- ❖ The primary-side current is made of the reflected i_L and i_{mag}



Primary-Side Current

The reflected output inductor current and the magnetizing current sum up



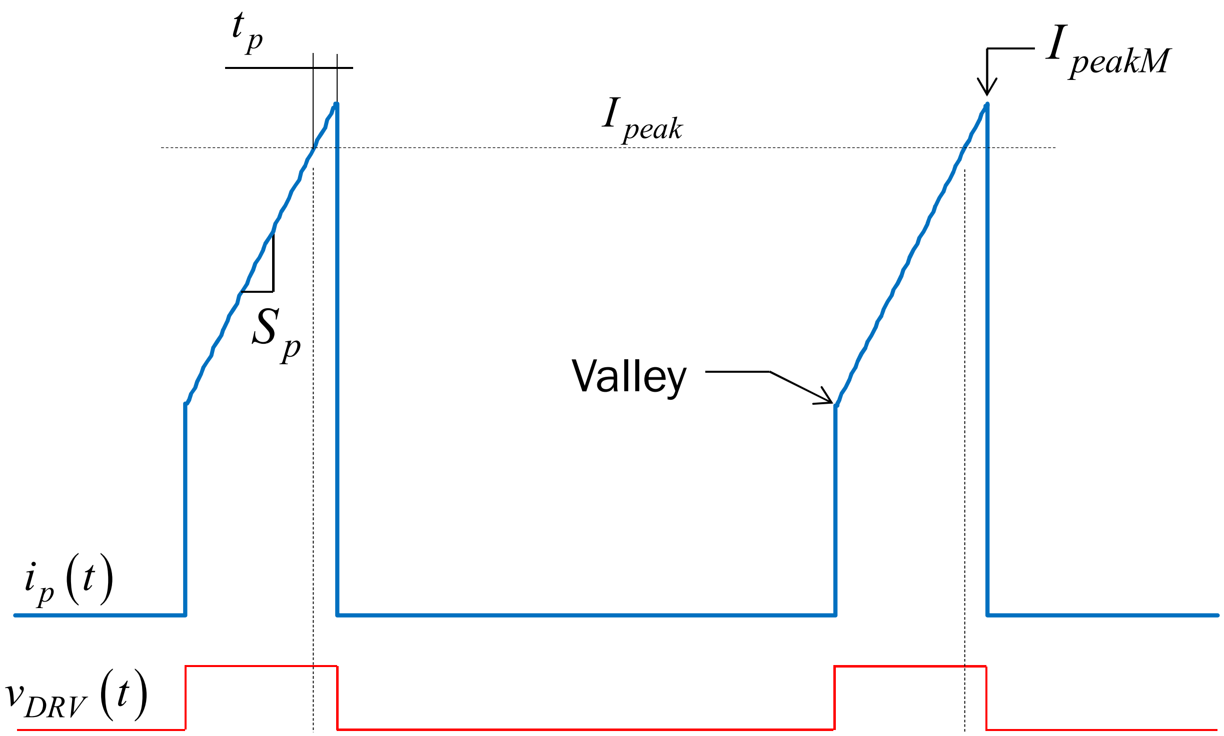
Primary Current when Current Limit is Active

$$S_{magLL} = \frac{V_{inLL}}{L_{mag}} \qquad S_{magHL} = \frac{V_{inHL}}{L_{mag}}$$

Mag current on-slopes

$$S_{onLL} = \frac{NV_{inLL} - V_{out}}{L_1} \qquad S_{onHL} = \frac{NV_{inHL} - V_{out}}{L_1}$$

Secondary current on-slopes

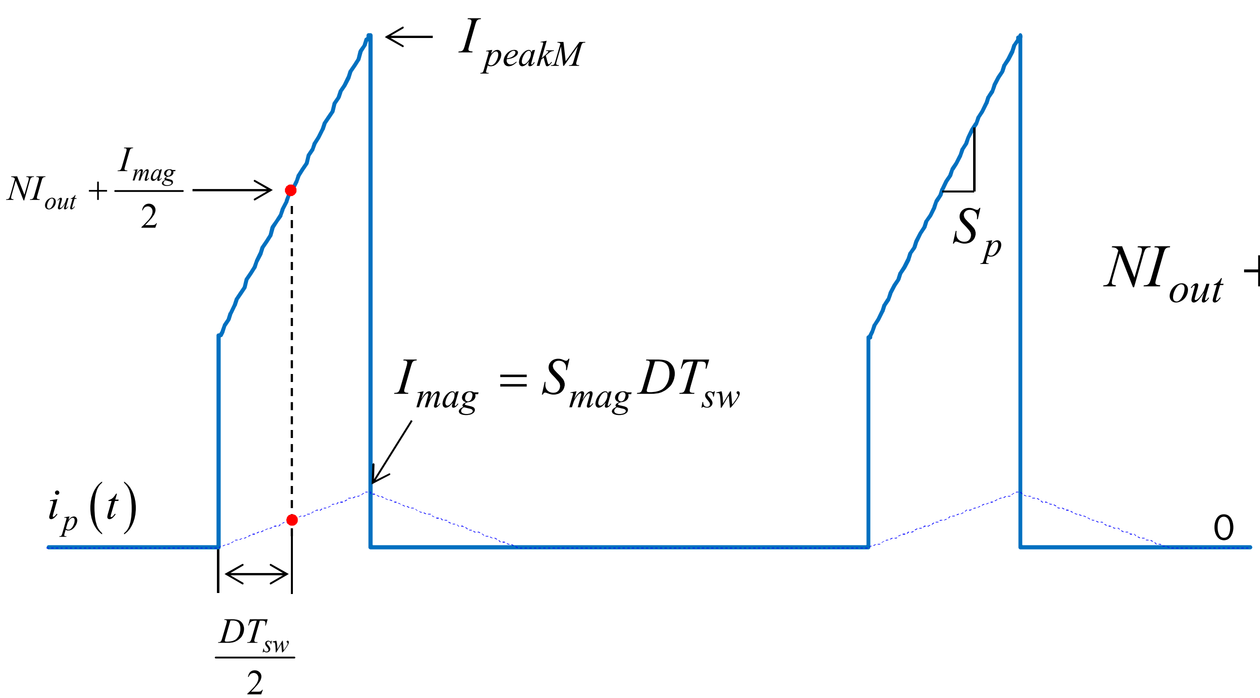


The MOSFET Current Primary Slope

It is the sum of the reflected output inductor current up slope with the mag. current slope:

$$S_{pHL} = S_{magHL} + NS_{onHL} \qquad S_{pLL} = S_{magLL} + NS_{onLL}$$

The output current can be computed from the total primary current i_p:



The equation to solve is:

$$NI_{out} + \frac{I_{mag}}{2} = I_{peakM} - S_p \frac{DT_{sw}}{2}$$

The Output Current when the Limit is Reached

$$I_{outLL} = \frac{2I_{peakMLL} - D_{LL}S_{pLL}T_{sw} - I_{magLL}}{2N} \qquad I_{outHL} = \frac{2I_{peakMHL} - D_{HL}S_{pHL}T_{sw} - I_{magHL}}{2N}$$

The final peak value is thus: $I_{peakLL} = I_{peakMLL} + S_{pLL}t_p \qquad I_{peakHL} = I_{peakMHL} + S_{pHL}t_p$

with $I_{peakMLL} = \frac{V_{\max}}{R_{sense}} \qquad I_{peakMHL} = \frac{V_{\max} - V_{opp}}{R_{sense}}$ ← offset

Develop and rearrange:

$$I_{outLL} = \frac{2\left[\frac{V_{\max}}{R_{sense}} + \left(\frac{V_{inLL}}{L_{mag}} + \frac{NV_{inLL} - V_{out}}{L}N\right)t_p\right] - D_{LL}\left(\frac{V_{inLL}}{L_{mag}} + \frac{NV_{inLL} - V_{out}}{L}N\right) - \frac{V_{in}}{L_{mag}}D_{LL}T_{sw}}{2N}$$

$$I_{outHL} = \frac{2\left[\frac{V_{\max} - V_{opp}}{R_{sense}} + \left(\frac{V_{inHL}}{L_{mag}} + \frac{NV_{inHL} - V_{out}}{L}N\right)t_p\right] - D_{HL}\left(\frac{V_{inHL}}{L_{mag}} + \frac{NV_{inHL} - V_{out}}{L}N\right) - \frac{V_{in}}{L_{mag}}D_{HL}T_{sw}}{2N}$$

LL = low line HL = high line

Subtract both Results to get ΔI_{out}

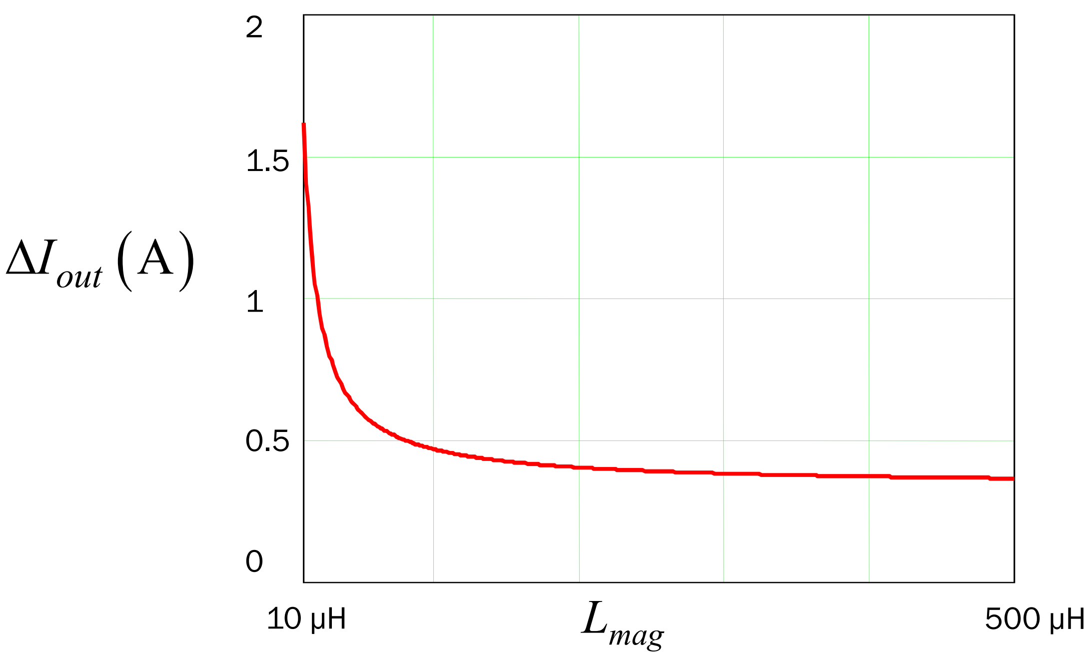
Prop delay

Subtract

OPP comp

$$\Delta I_{out} = I_{outHL} - I_{outLL}$$

$$\Delta I_{out} = V_{inLL}\left(\frac{D_{LL}T_{sw} - t_p}{NL_{mag}} - \frac{2Nt_p - D_{LL}NT_{sw}}{2L_1}\right) + V_{inHL}\left(\frac{t_p - D_{HL}T_{sw}}{NL_{mag}} + \frac{2Nt_p - D_{HL}NT_{sw}}{2L_1}\right) + \frac{V_{out}T_{sw}}{2L_1}\left(D_{HL} - D_{LL}\right) - \frac{V_{opp}}{NR_{sense}}$$



The magnetizing current proportionally increases the output error between hi- and lo-line conditions.

How Much OPP Offset?

Solve the V_{opp} value which brings a 0-A ΔI_{out}:

$$\Delta I_{out}\left(V_{opp}\right)=0$$

$$V_{opp}=\frac{R_{sense}\left[V_{inHL}\left(2L_1t_p+2L_{mag}N^2t_p-2D_{HL}L_1T_{sw}-D_{HL}L_{mag}N^2T_{sw}\right)+V_{inLL}\left(2D_{LL}L_1T_{sw}-2L_{mag}N^2t_p-2L_1t_p+D_{LL}L_{mag}N^2T_{sw}\right)+L_{mag}NT_{sw}V_{out}\left(D_{HL}-D_{LL}\right)\right]}{2L_1L_{mag}}$$

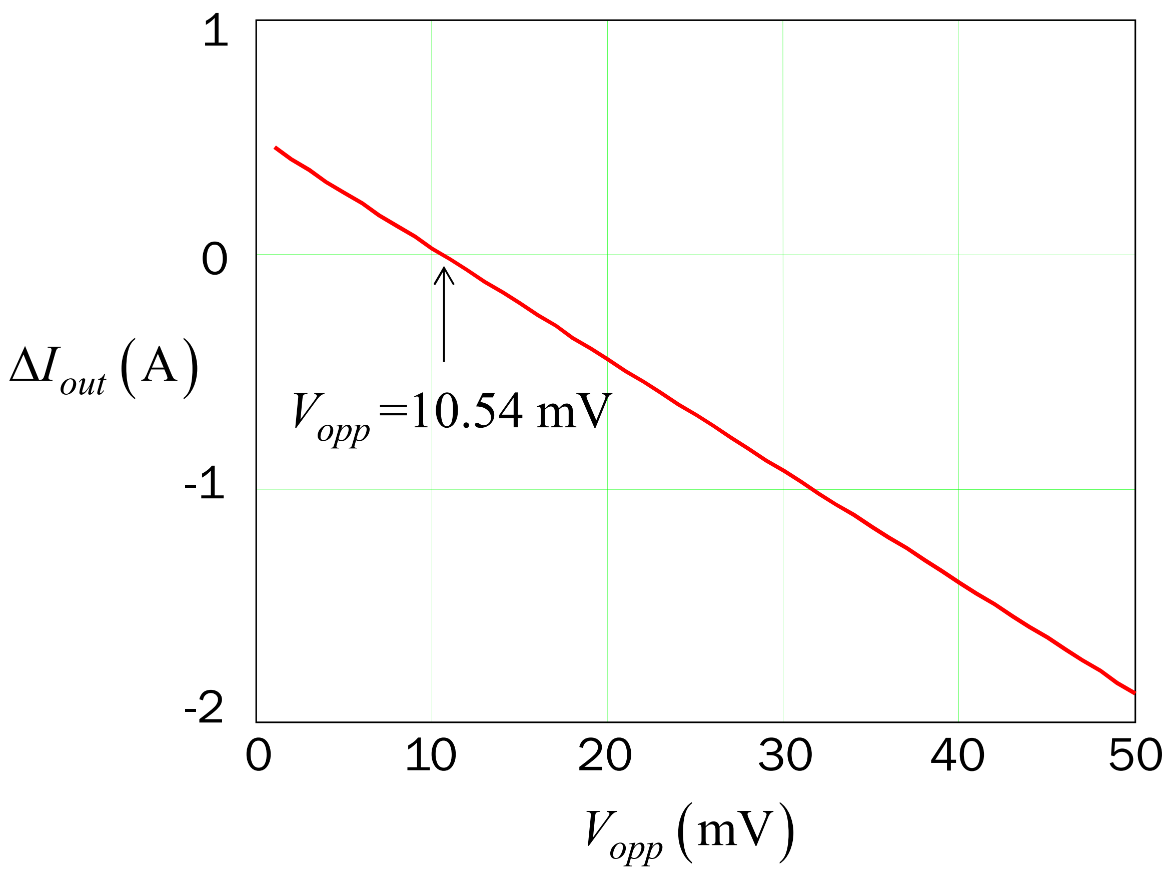
Let's see some numerical application now. We consider a 10-A forward converter operating at a 100-kHz switching frequency – V_{opp} = 0:

$$F_{sw}=100\text{ kHz}\qquad R_{sense}=35\text{ m}\Omega$$
$$L_{mag}=80\ \mu\text{H}\qquad V_{sense}=0.4\text{ V}$$
$$L_1=5\ \mu\text{H}\qquad V_{out}=5\text{ V}$$
$$t_p=213\text{ ns}\quad V_{opp}=0\text{ V}$$

$$\Rightarrow\quad I_{outLL}=14.33\text{ A}\qquad I_{outHL}=14.8\text{ A}$$

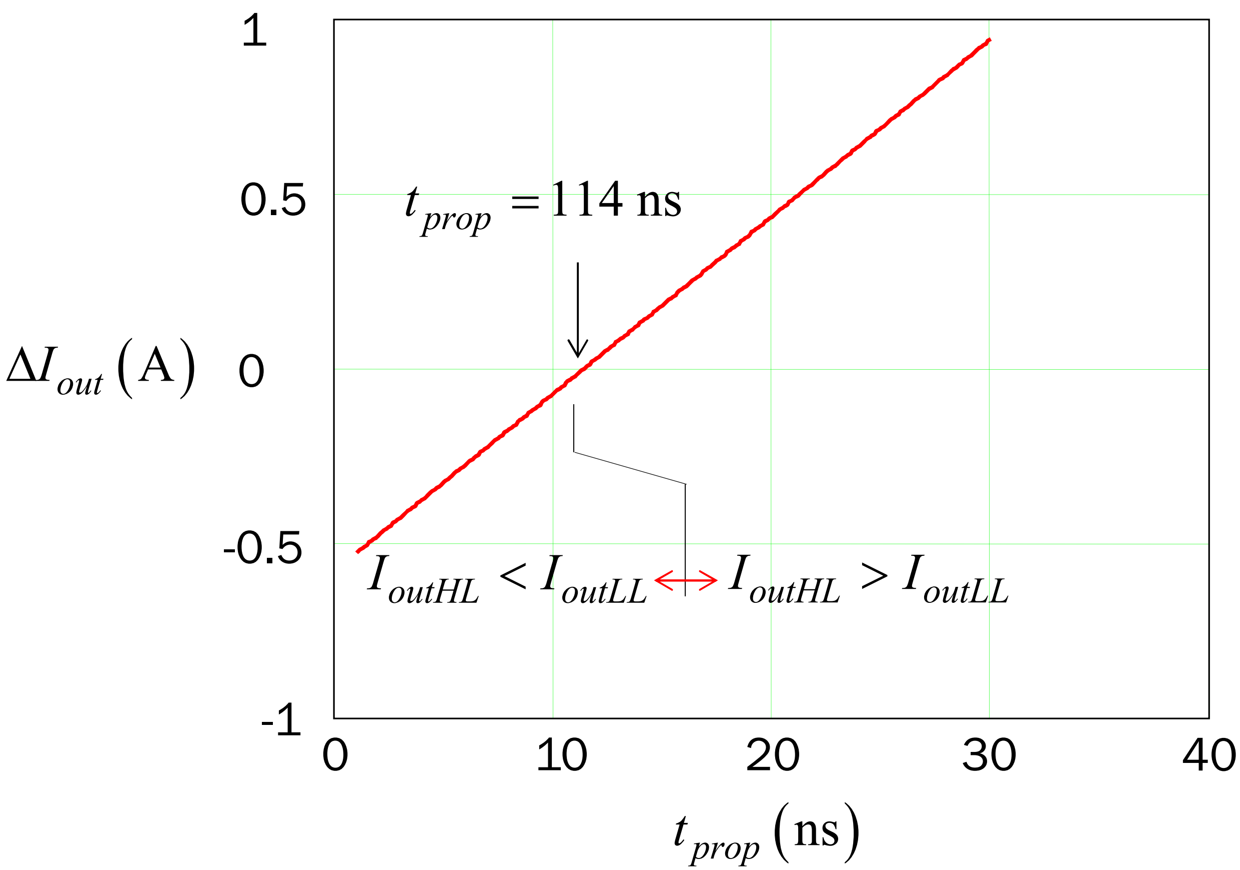
Adding an Offset on the CS Pin

By injecting the exact amount of OPP on the CS pin, the LL-HL error disappears



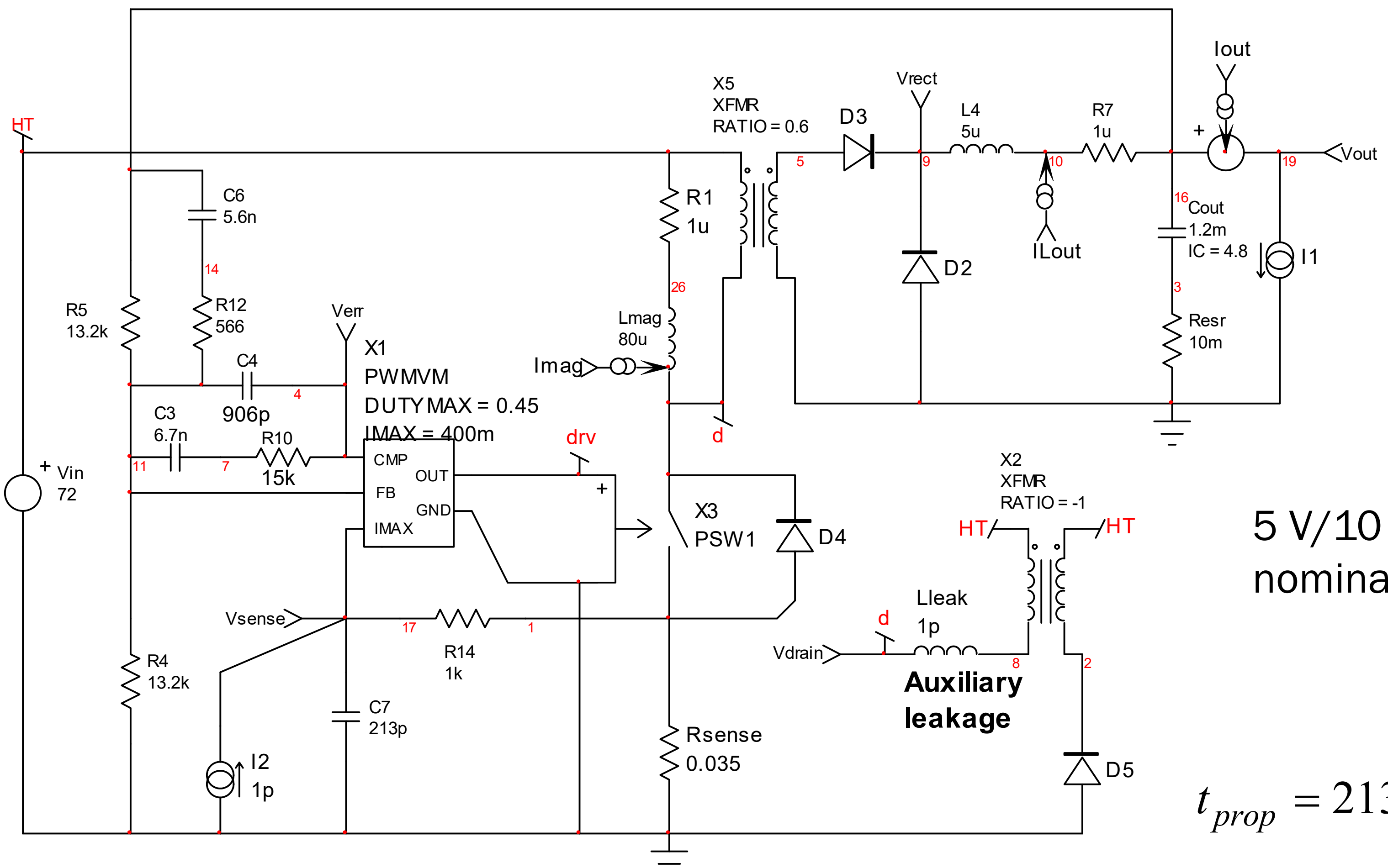
The Error Depends on the Prop. Delay

The propagation delay plays a role in the current difference and too fast a controller can reverse the difference polarity.



Simulation File

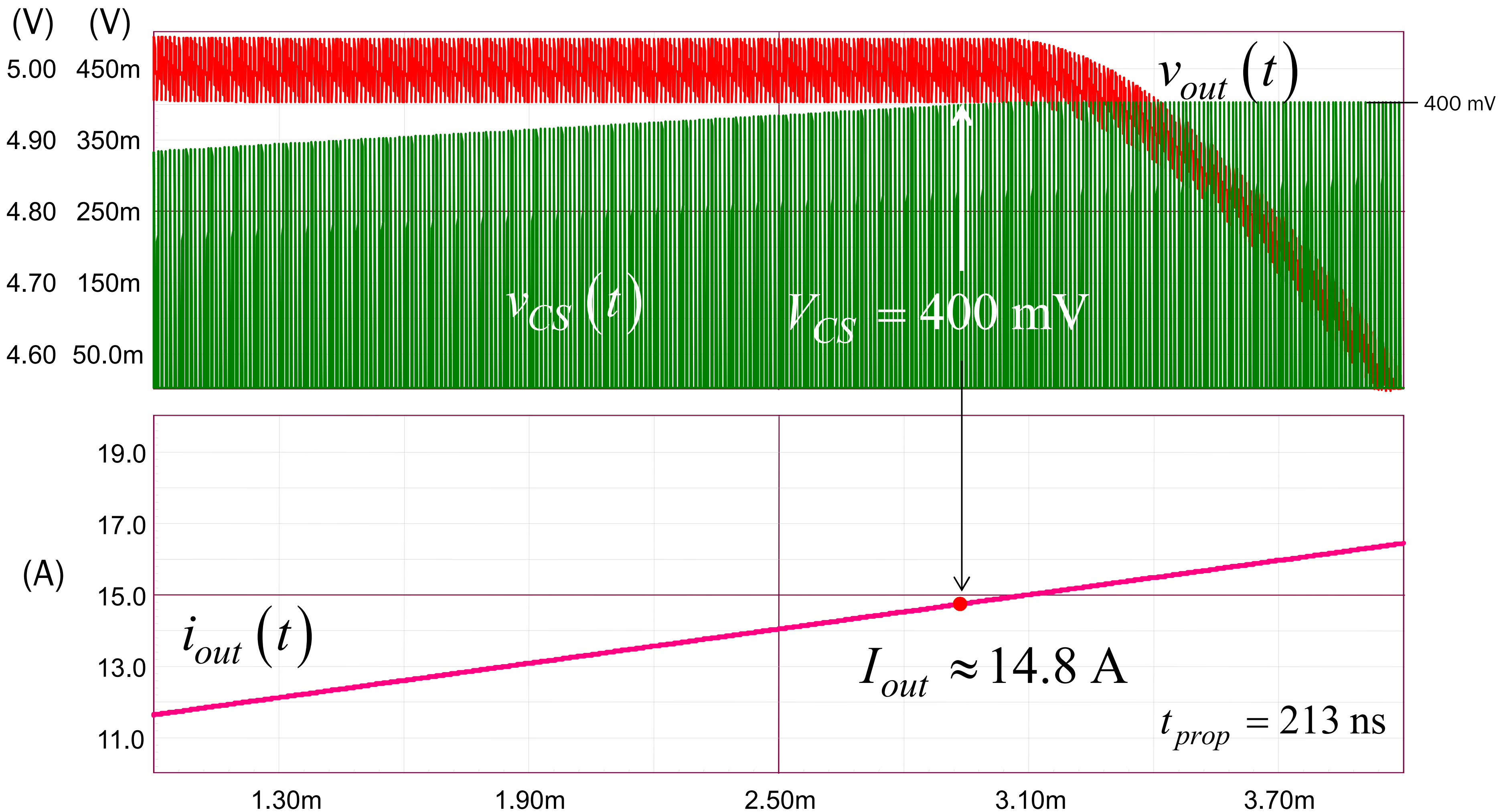
Simulation circuit for a 36-72-V input voltage range



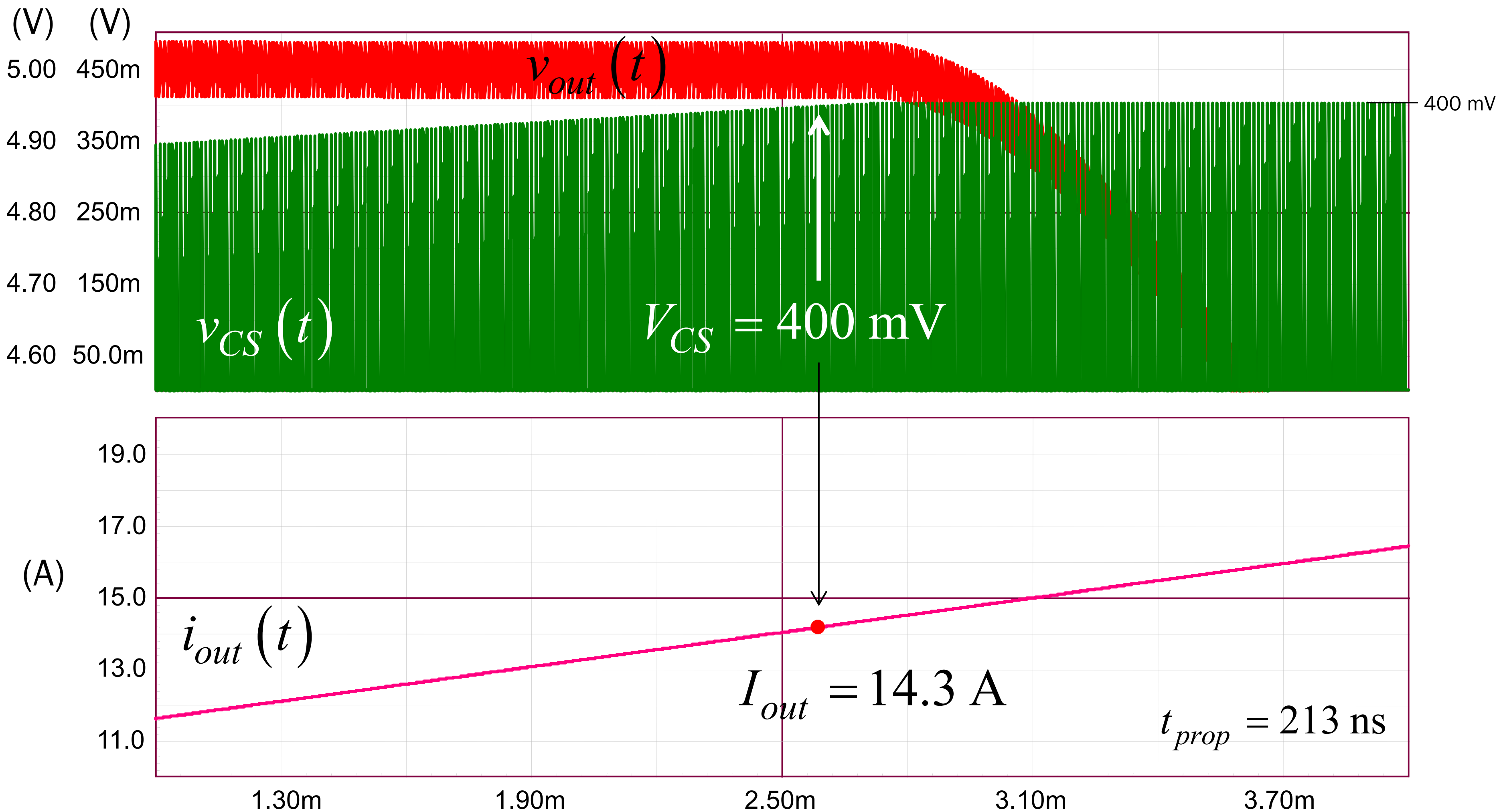
5 V/10 A
nominal

$$t_{prop} = 213\ ns$$

Simulation Results High Line

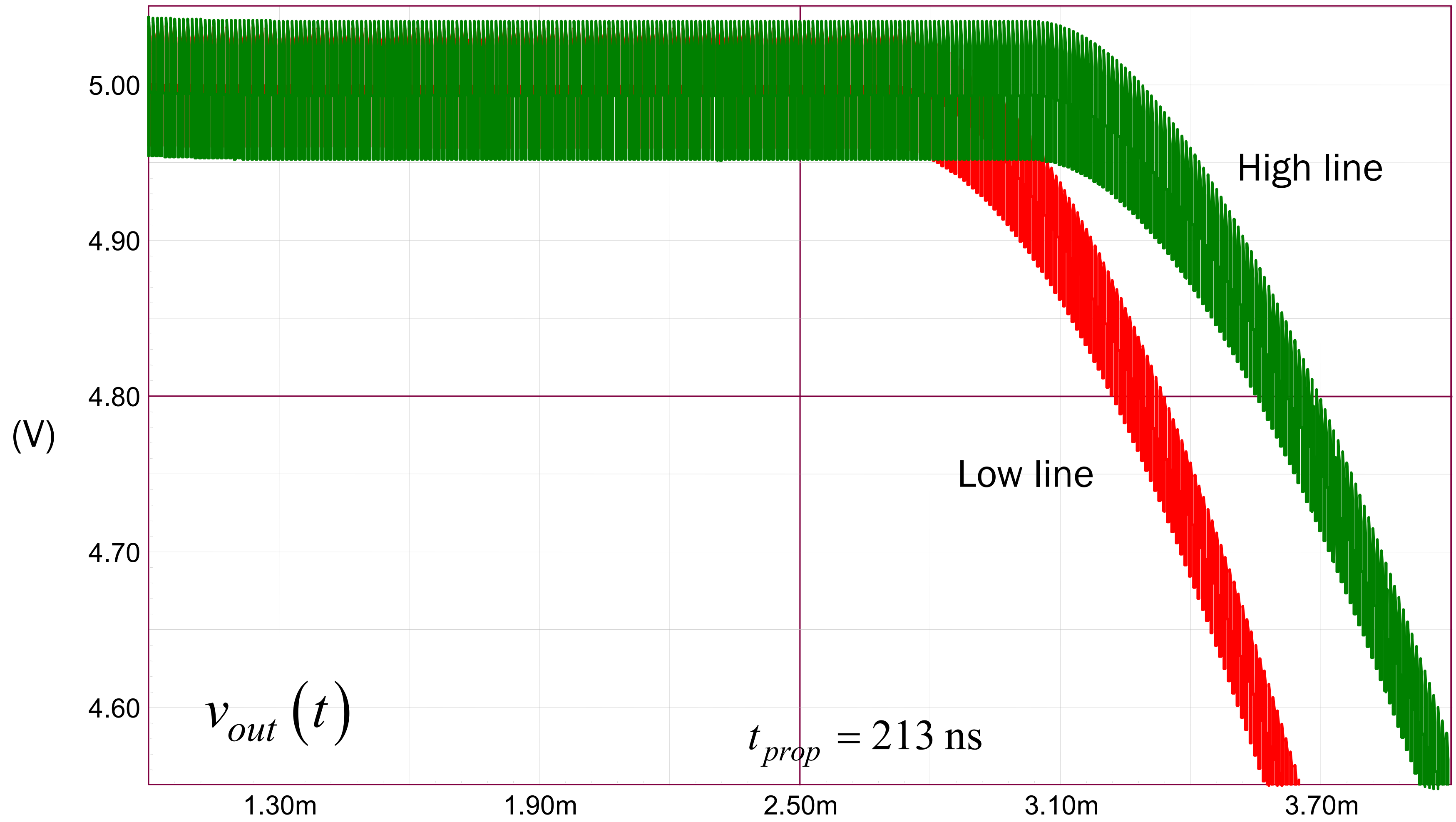


Simulation Results Low Line



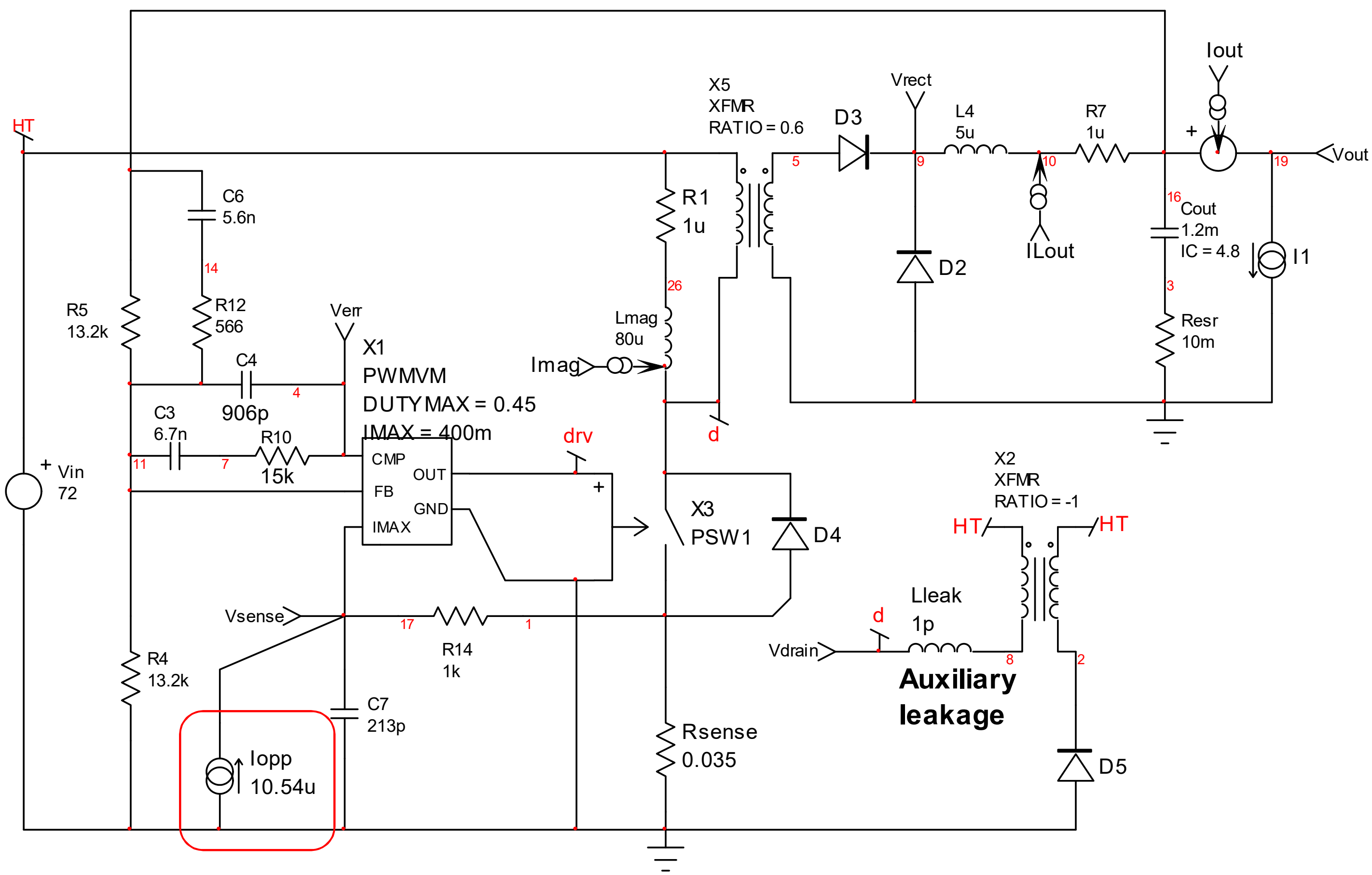
Simulation Results

In this case, the maximum output current is larger in HL than in LL



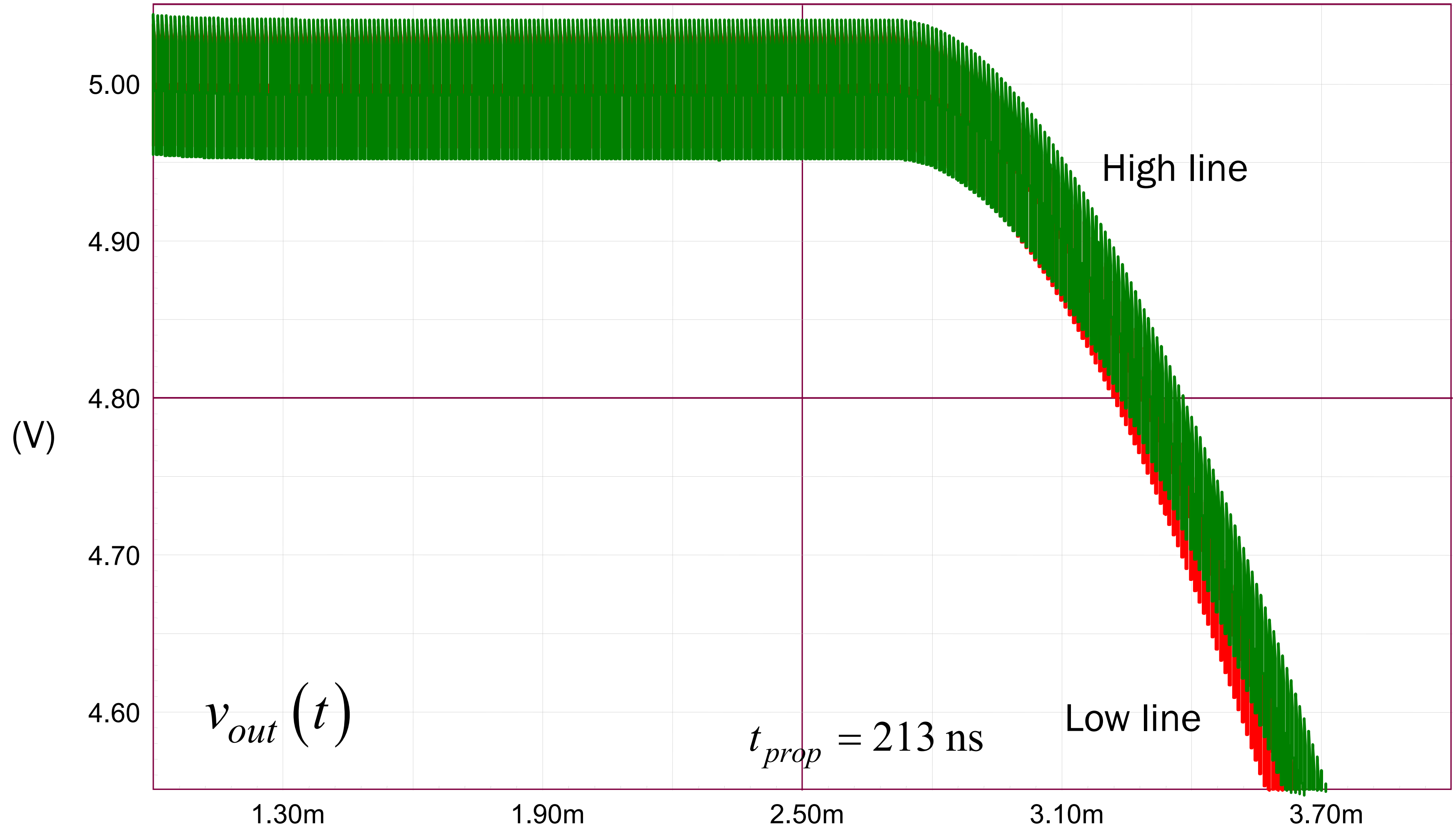
Inject the Exact OPP Level

Calculations recommend a V_{OPP} of 10.54 mV – 10.54 µA into the 1-k resistance



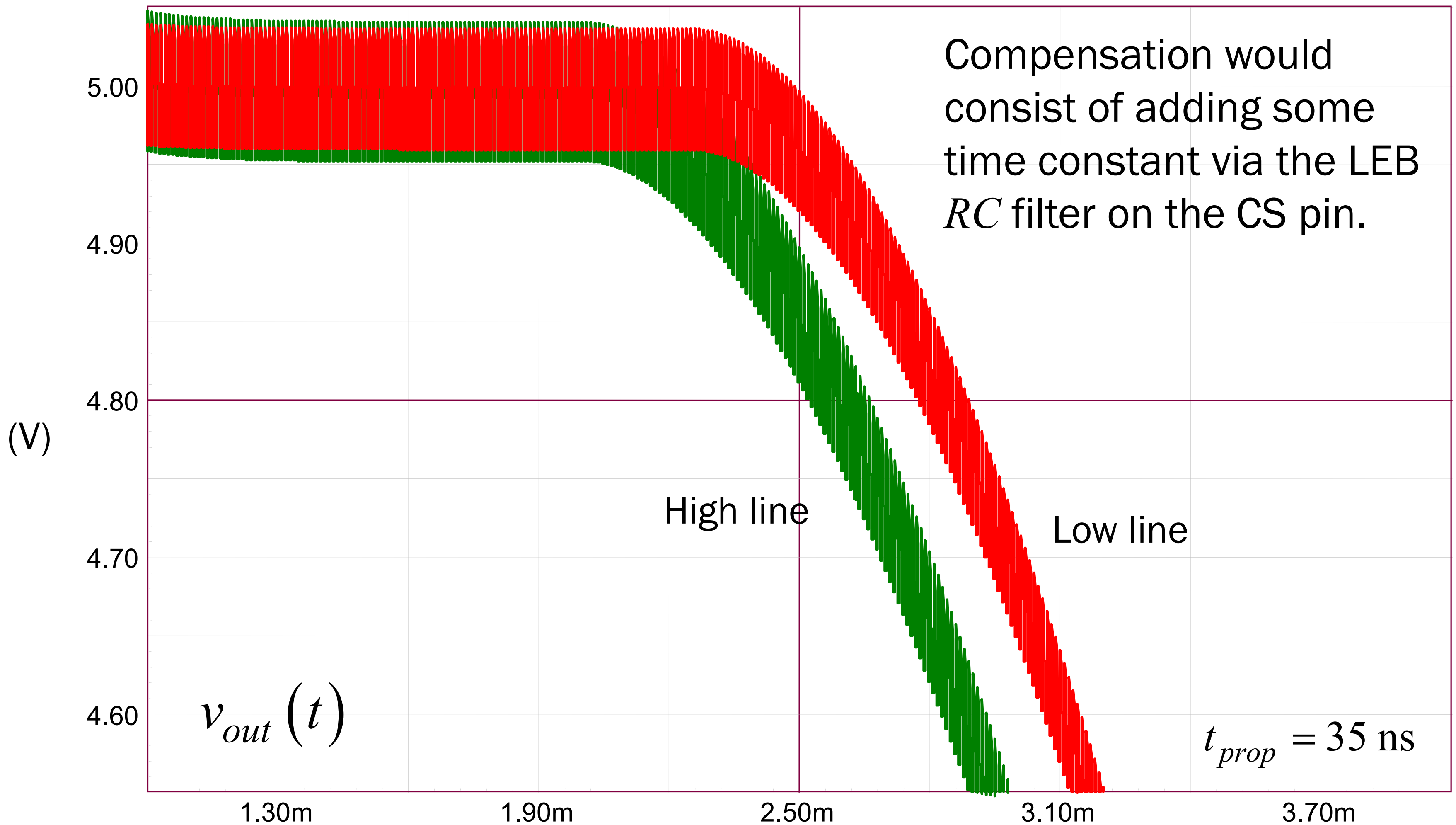
Compensated Case

In this compensated case, the current capability LL and HL is identical



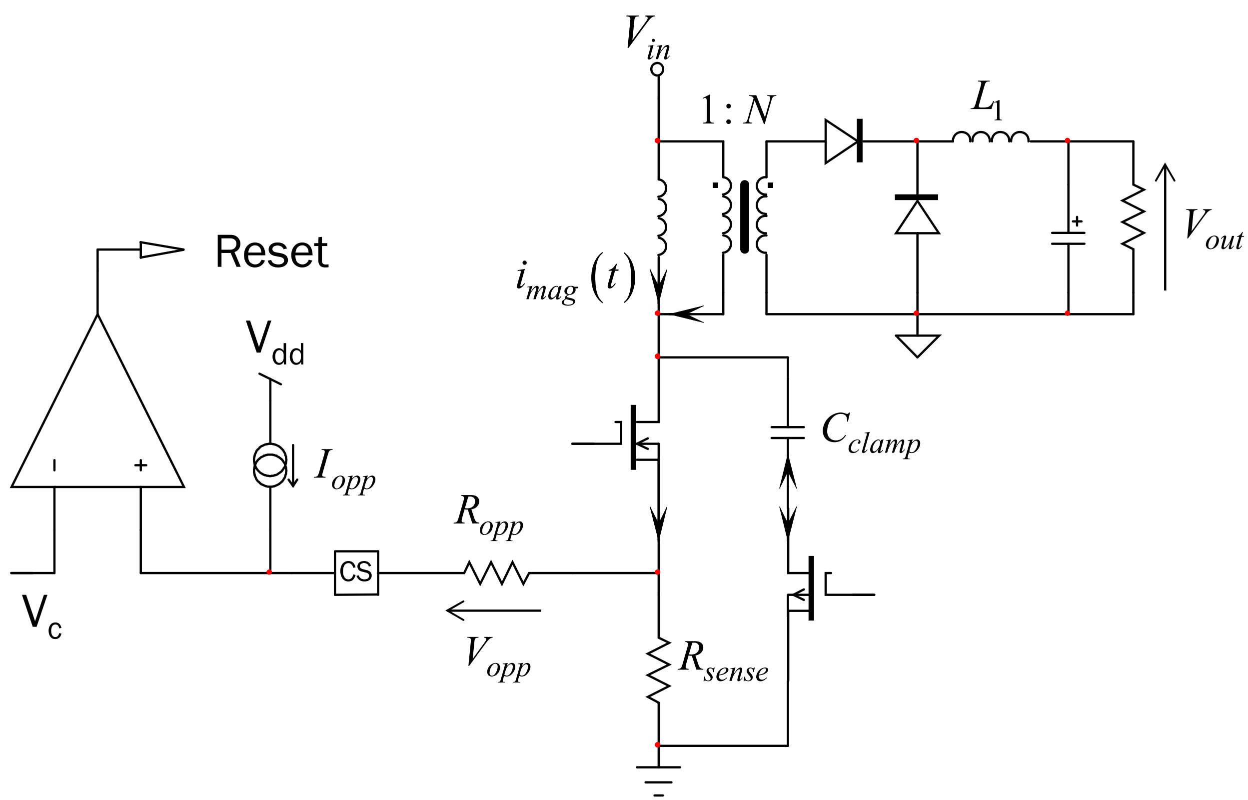
A Fast Controller – No OPP

In this faster controller case, the current capability LL is larger than in HL



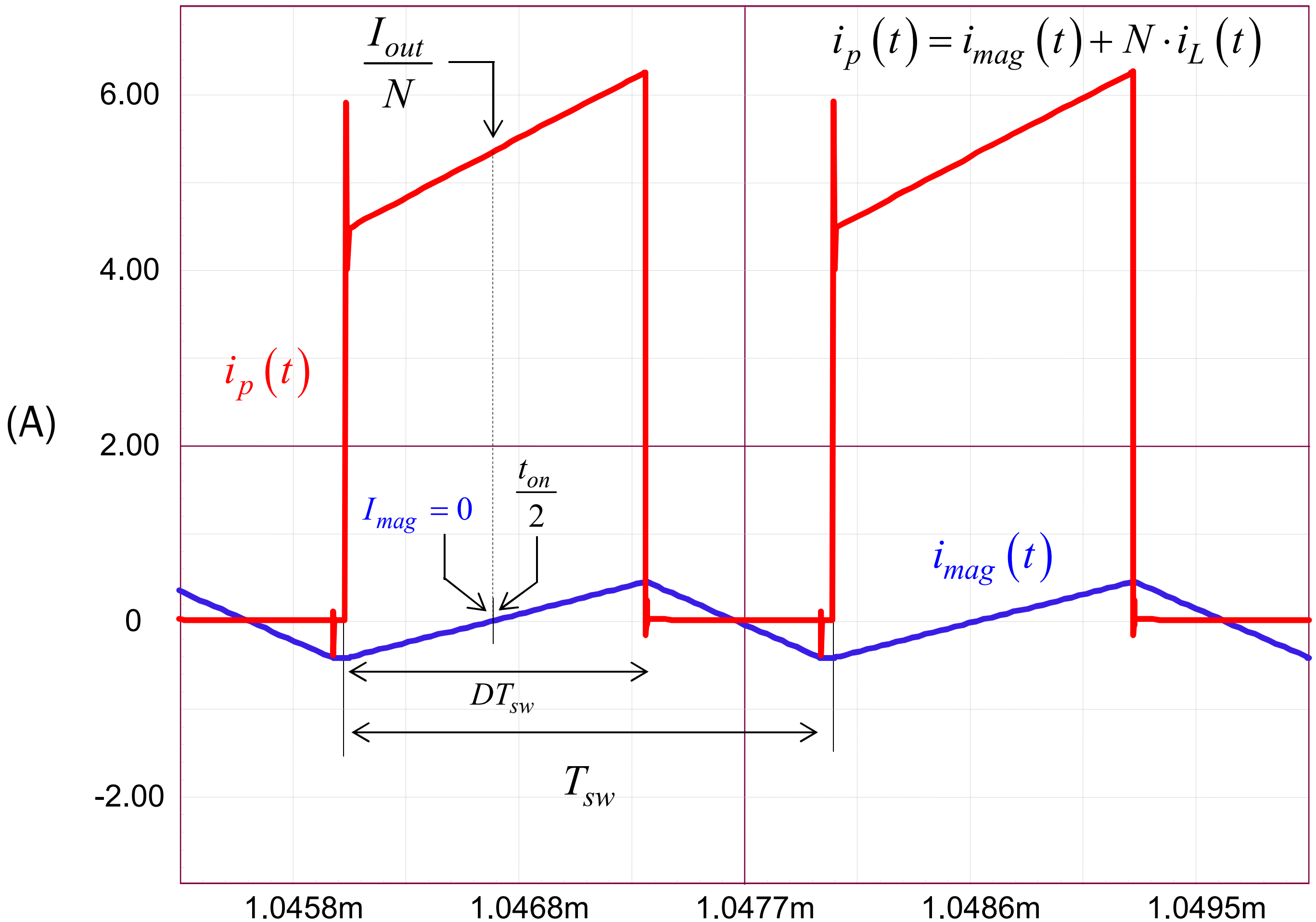
The Active Clamp Case

In a ACF, the situation differs as the mag. current is centered around 0 at steady-state.



The Average Magnetizing Current is 0

In the current expression we have derived, set I_{mag} to 0 and solve for I_{out}.



Output Current Definition

$$I_{outLL} = \frac{I_{peakMLL} - S_{pLL}\left(\frac{D_{LL}T_{sw} + t_p}{2}\right)}{N} \qquad I_{outHL} = \frac{I_{peakMHL} - S_{pHL}\left(\frac{D_{HL}T_{sw} + t_p}{2}\right)}{N}$$

$$I_{outLL} = \frac{\frac{V_{\max}}{R_{sense}} + \left(\frac{V_{inLL}}{L_{mag}} + \frac{NV_{inLL} - V_{out}}{L_1}N\right)\left(t_p - \frac{D_{LL}T_{sw}}{2}\right)}{N}$$

$$I_{outHL} = \frac{\frac{V_{\max} - V_{opp}}{R_{sense}} + \left(\frac{V_{inHL}}{L_{mag}} + \frac{NV_{inHL} - V_{out}}{L_1}N\right)\left(t_p - \frac{D_{HL}T_{sw}}{2}\right)}{N}$$

A 30-A Active Clamp Forward Converter

We consider a 30-A active clamp forward converter operating at a 500-kHz switching frequency:

Low-line is higher than HL!

$$F_{sw} = 500\ \text{kHz} \qquad R_{sense} = 60\ \text{m}\Omega$$

$$L_{mag} = 50\ \mu\text{H} \qquad V_{sense} = 0.4\ \text{V}$$

$$L_1 = 0.5\ \mu\text{H} \qquad V_{out} = 3.3\ \text{V}$$

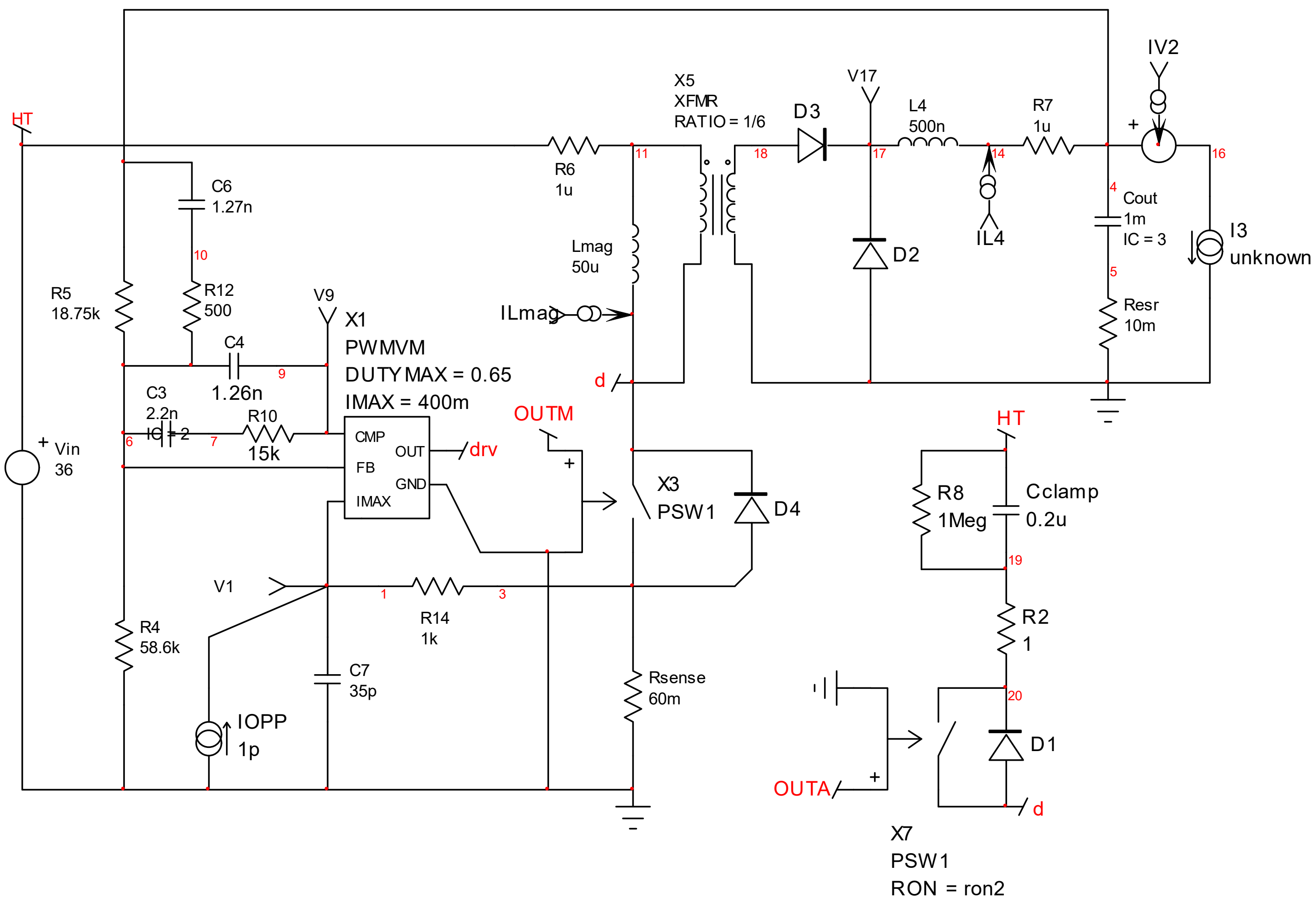
$$t_p = 35\ \text{ns}\ V_{opp} = 0\ \text{V}$$

$$I_{outLL} \approx 35\ \text{A}$$

$$I_{outHL} = 33.75\ \text{A}$$

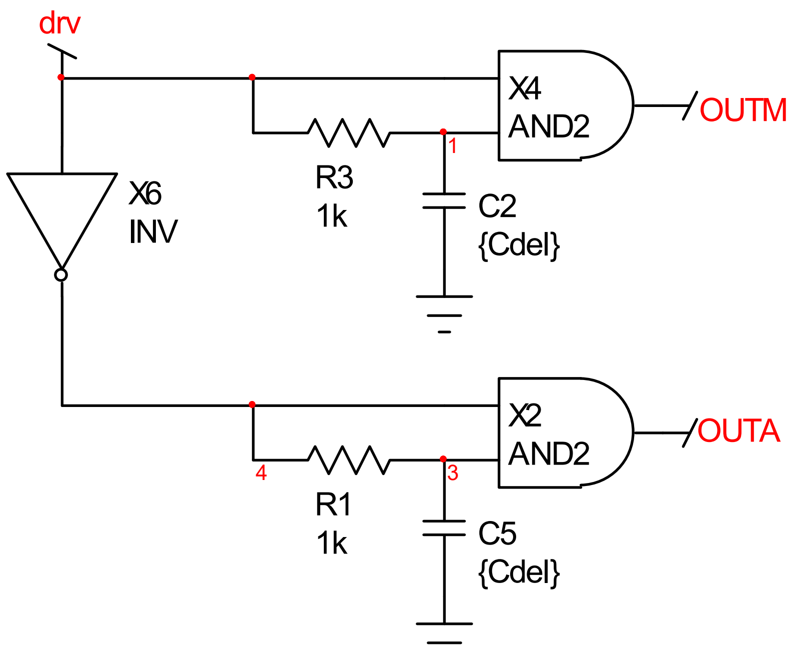
Simulation Schematic – Part I

This ACF operates a 500-kHz switching frequency



Simulation Schematic – Part II

The ACF requires some dead time between the drives to ensure near-ZVS operation.



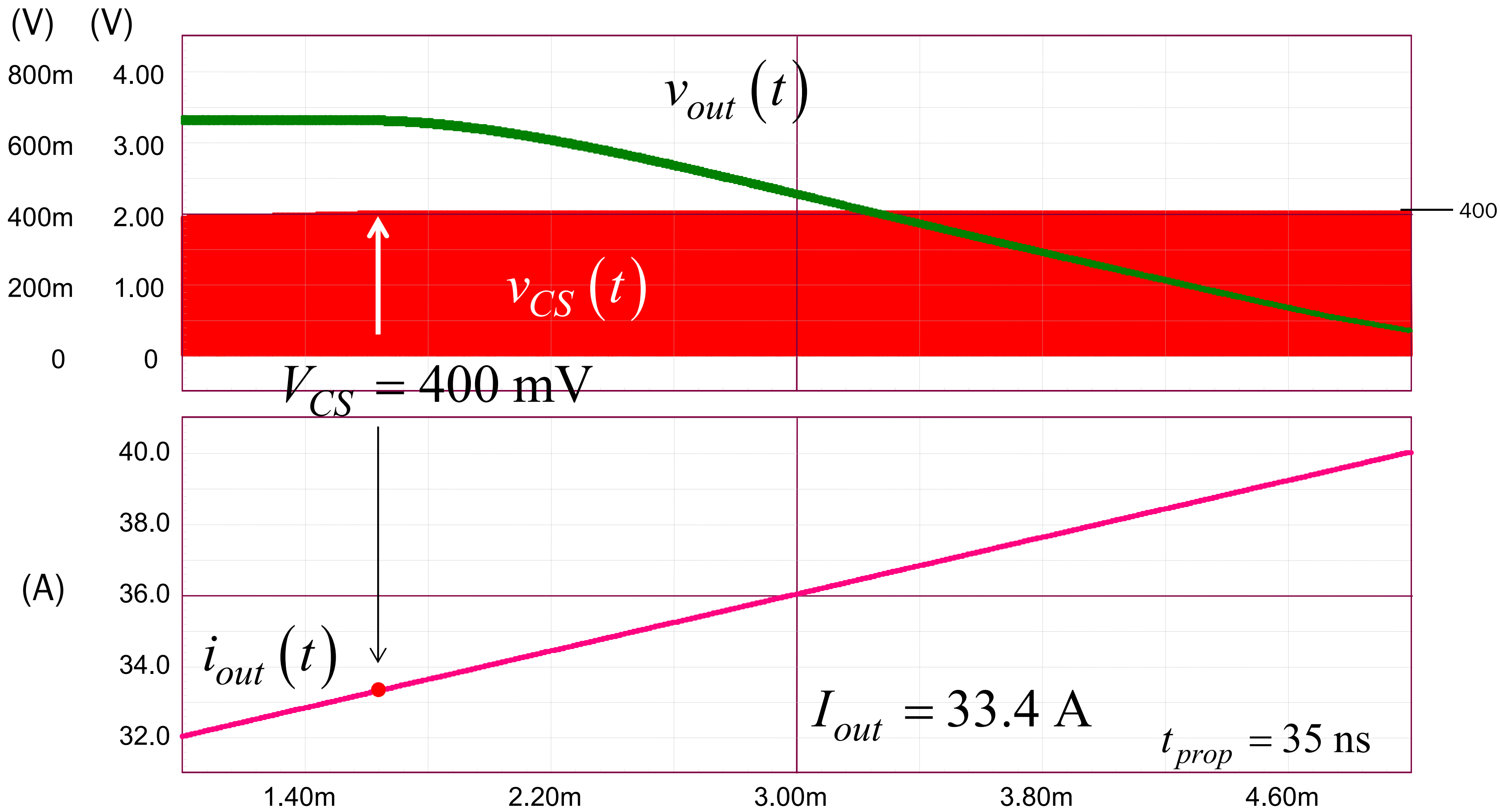
parameters

Fsw=500k
Tsw=1/Fsw

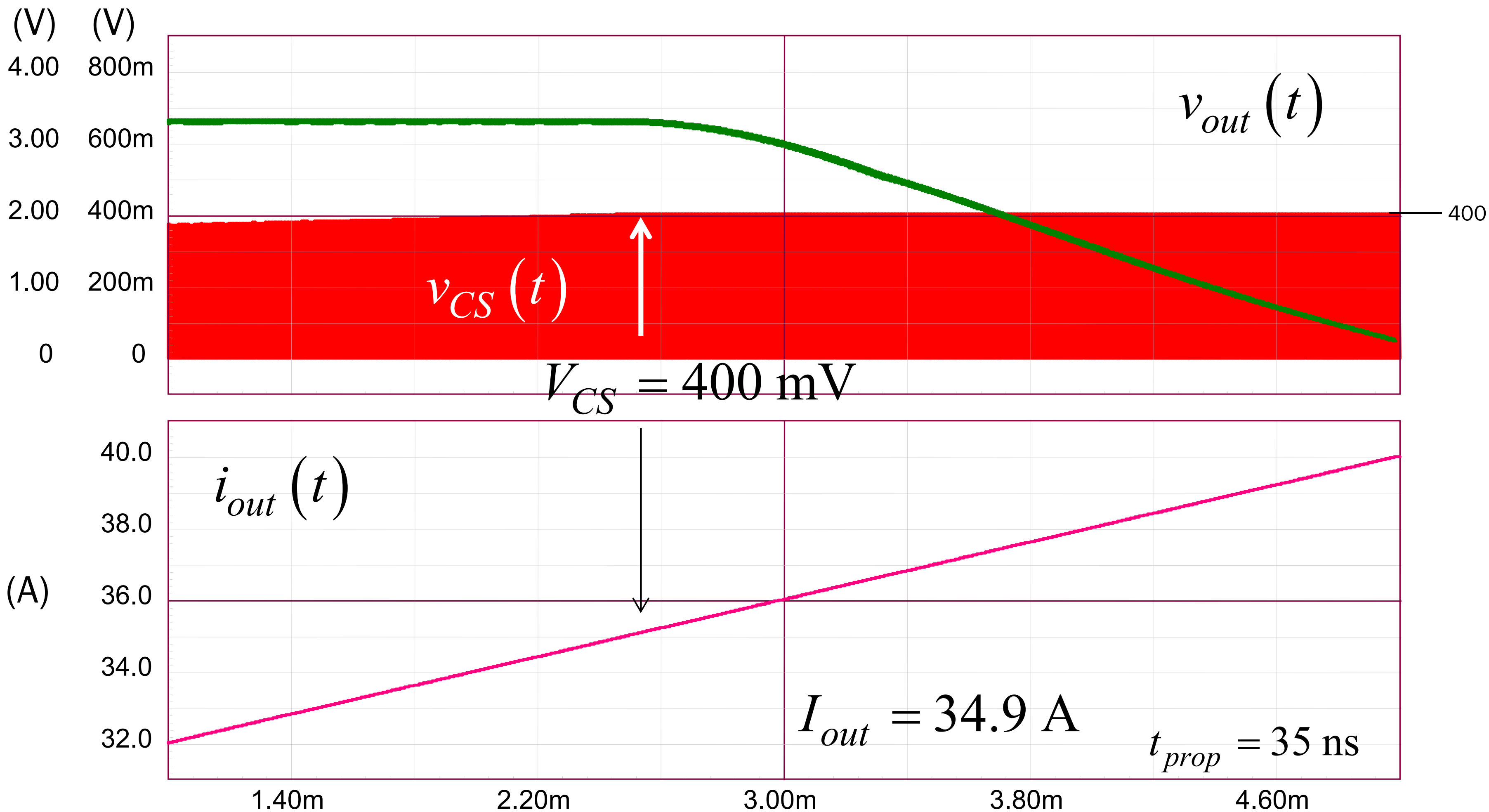
del=50n
Cdel=del/(0.693*1k)

N=1/6
ron1=60m
ron2=60m

Simulation Results High Line

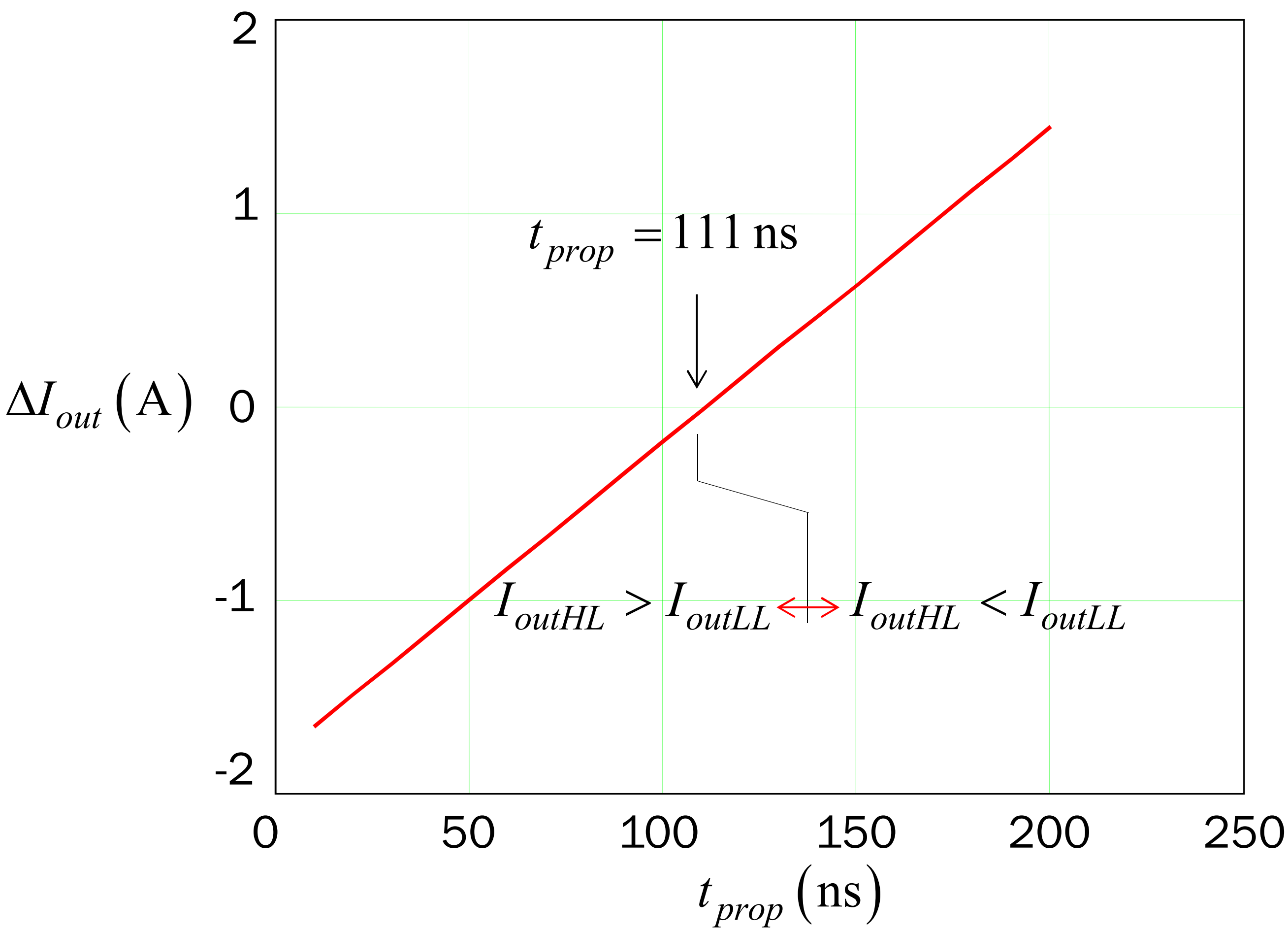


Simulation Results Low Line

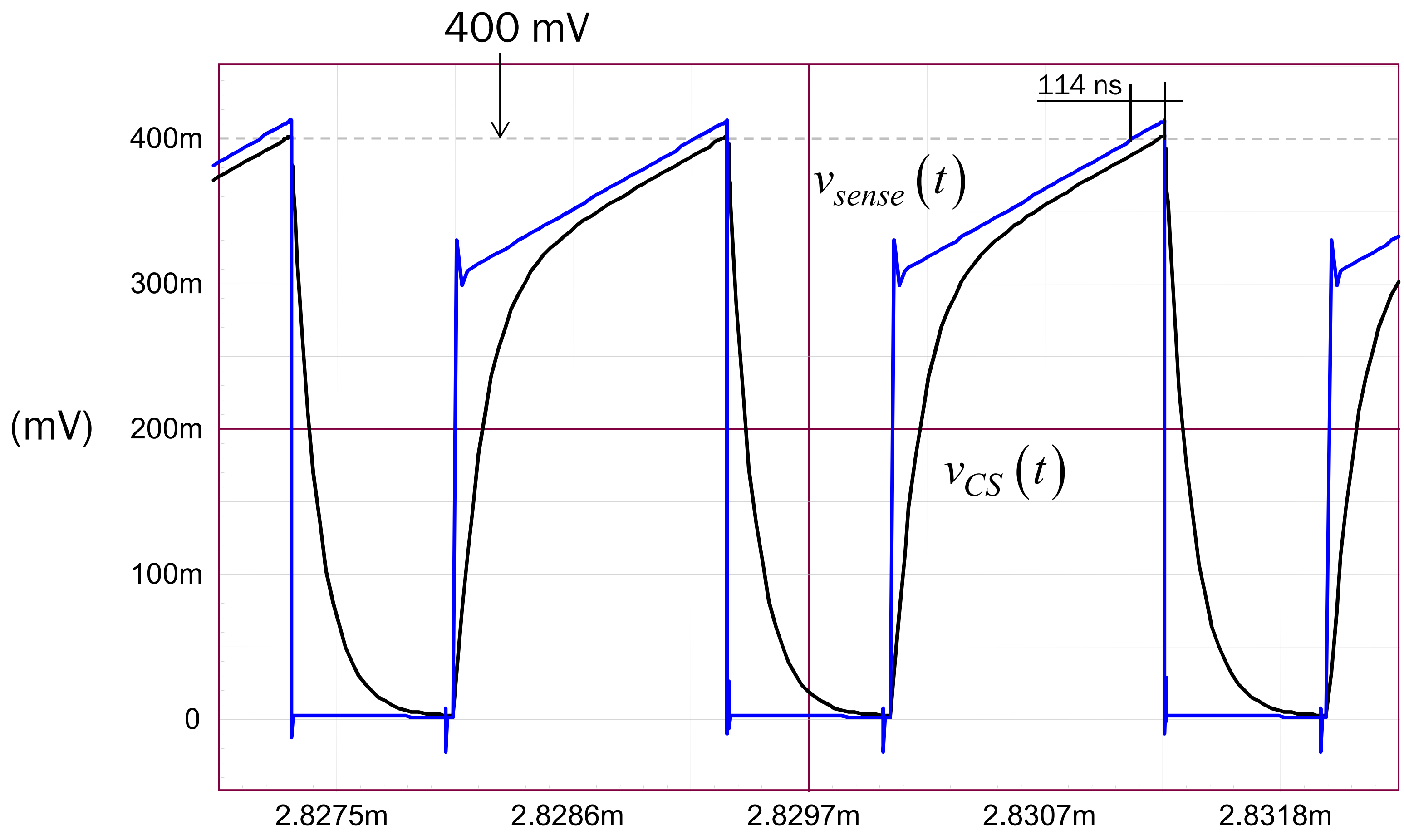


Check Propagation Delay versus I_{out}

You can make the controller slightly slower to match LL and HL output currents



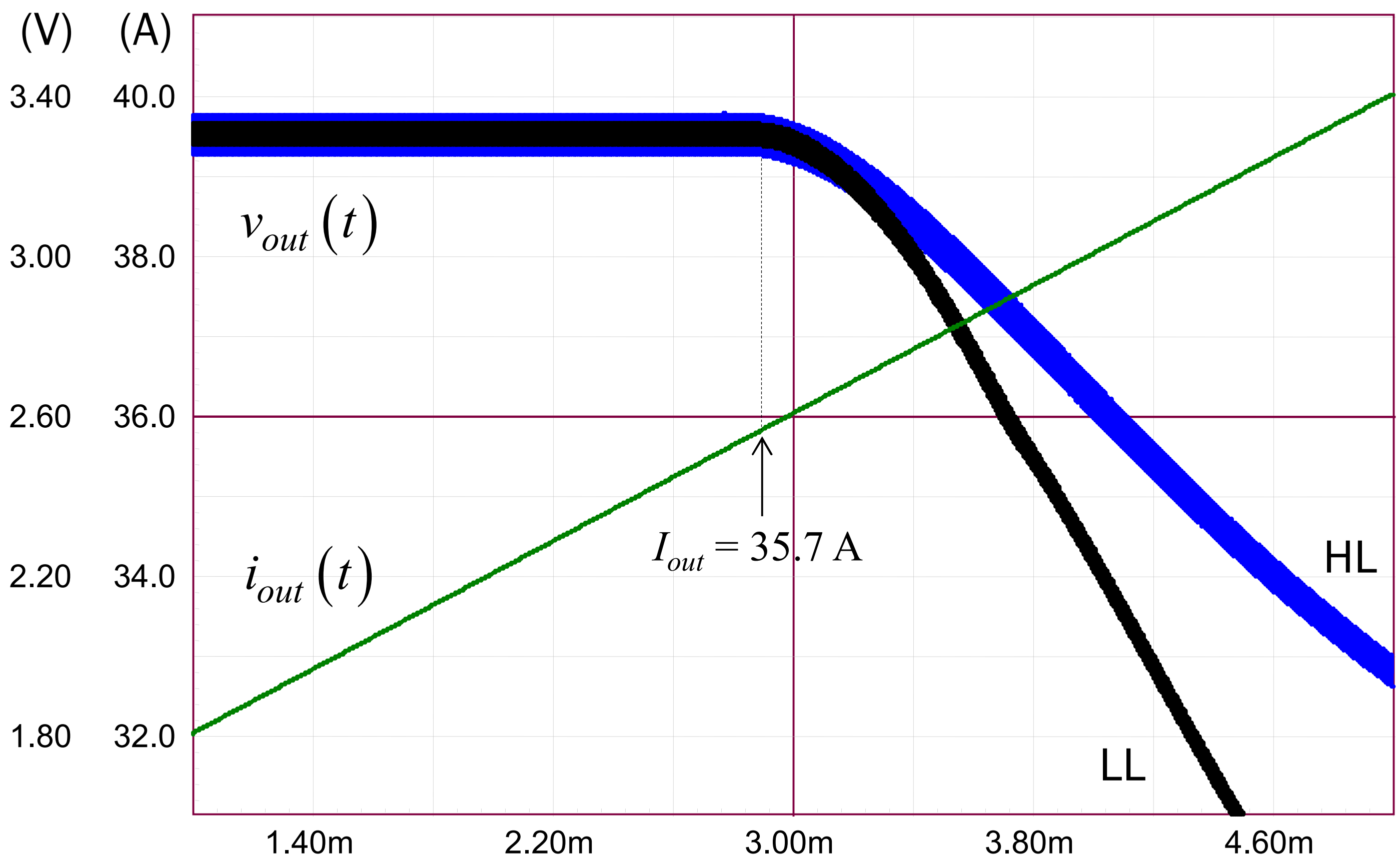
ACF with Compensated Prop. Delay



C_{CS} = 150 pF

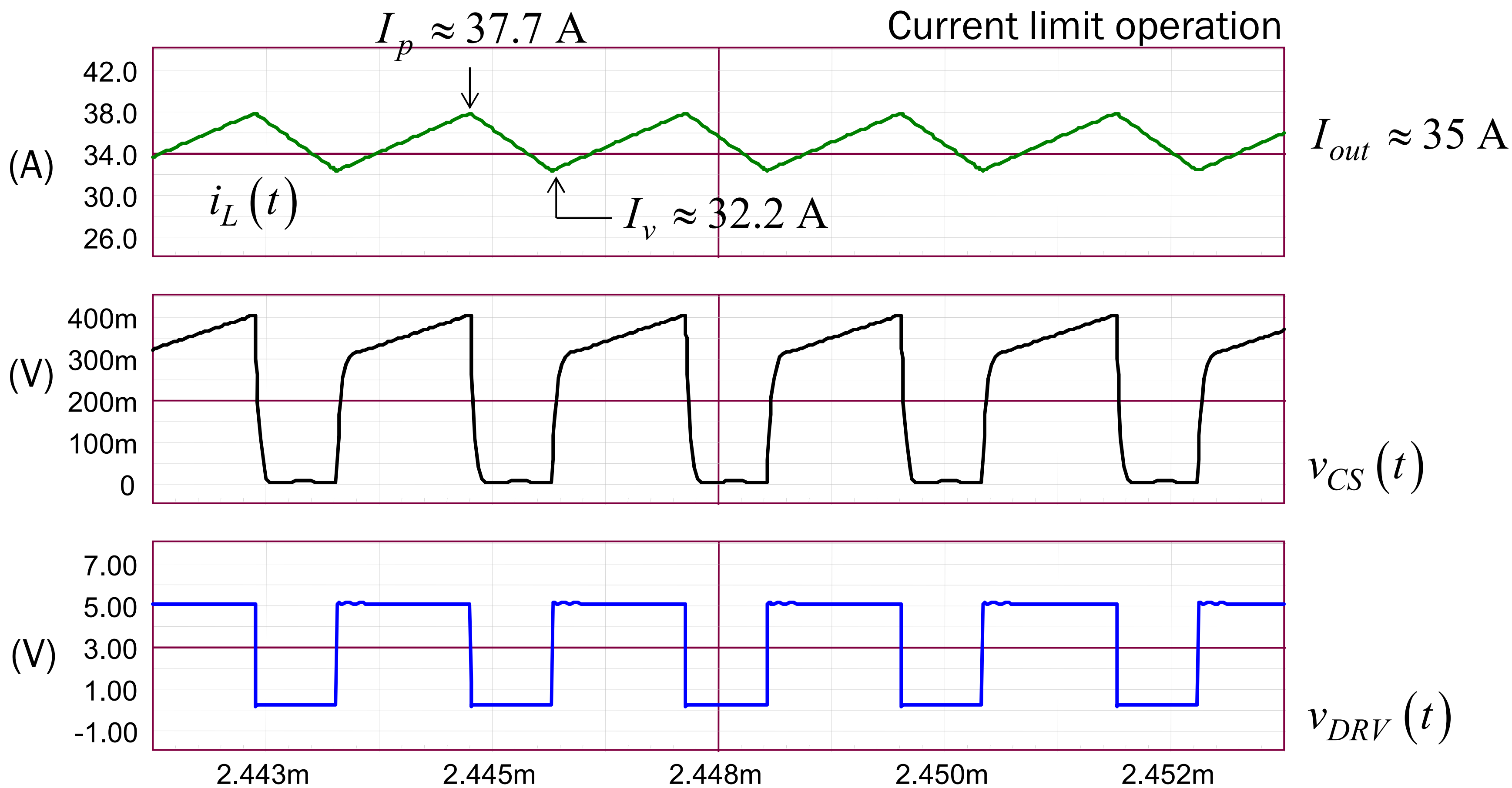
Compensated Converter

Maximum current trip points are now almost identical after compensation



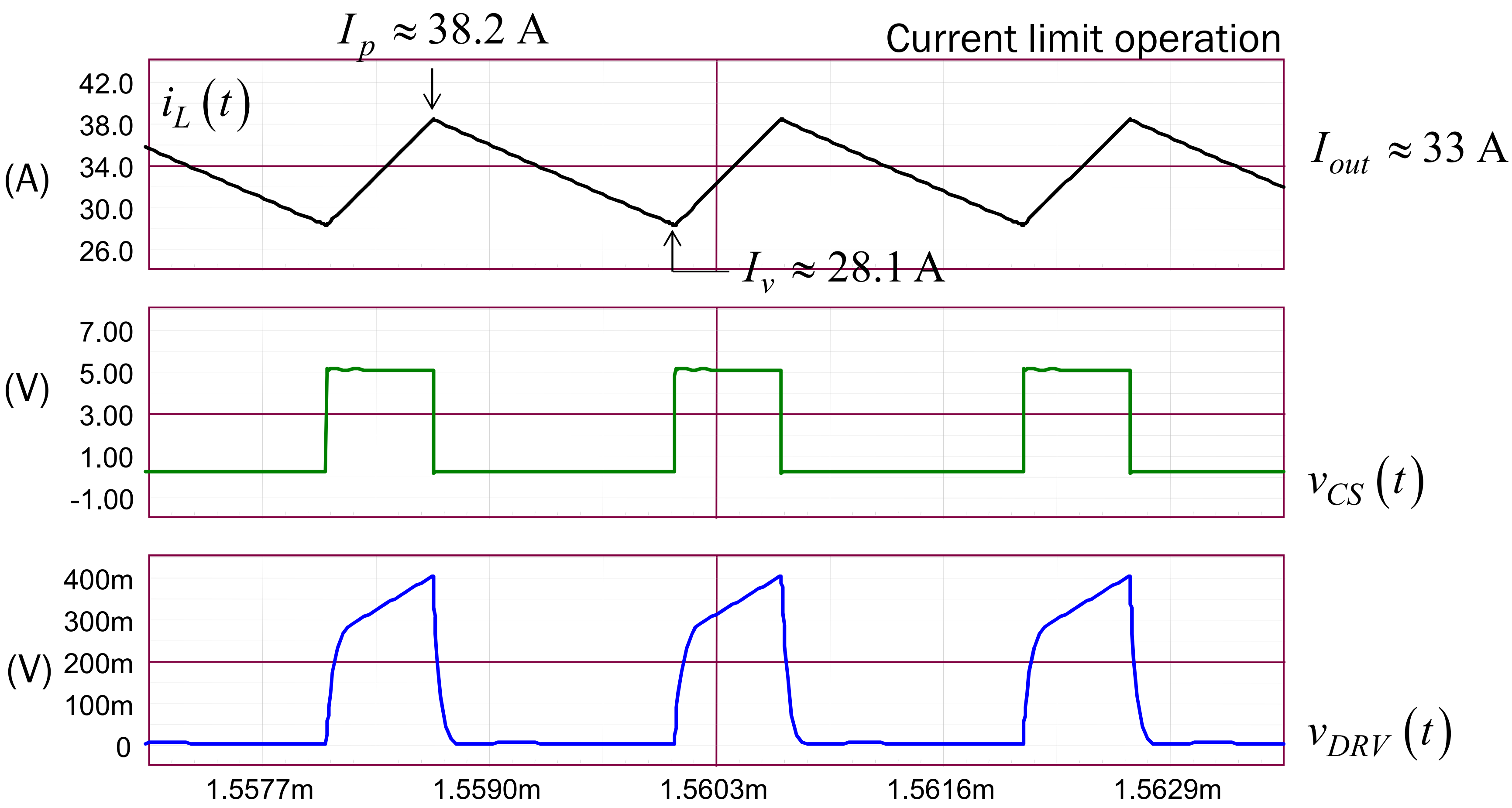
Low-Line Waveforms

In low-line conditions, the smaller t_{off} limits the inductor demagnetization time



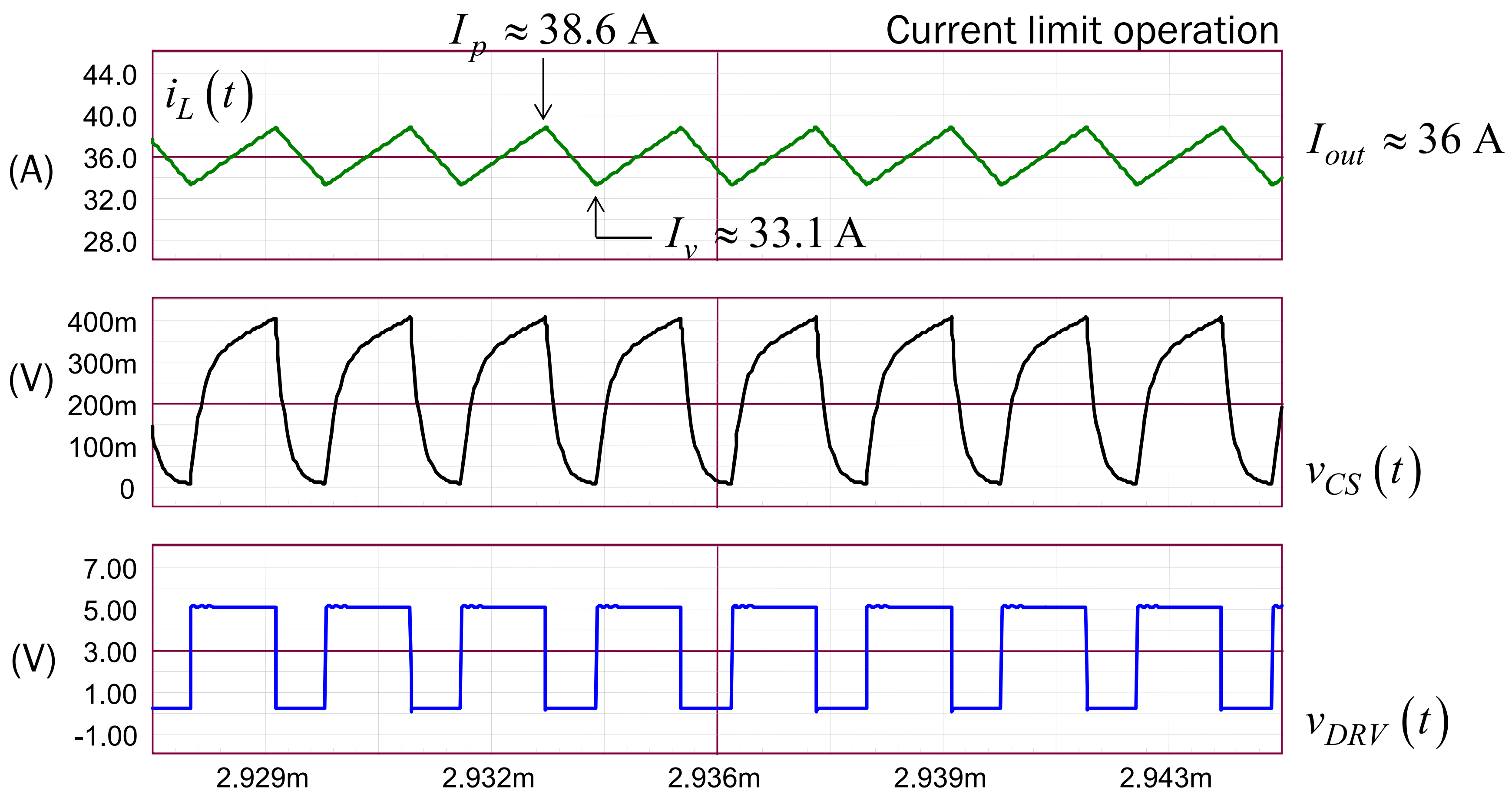
High-Line Waveforms

In high-line conditions, the larger t_{off} induces a lower inductor valley current



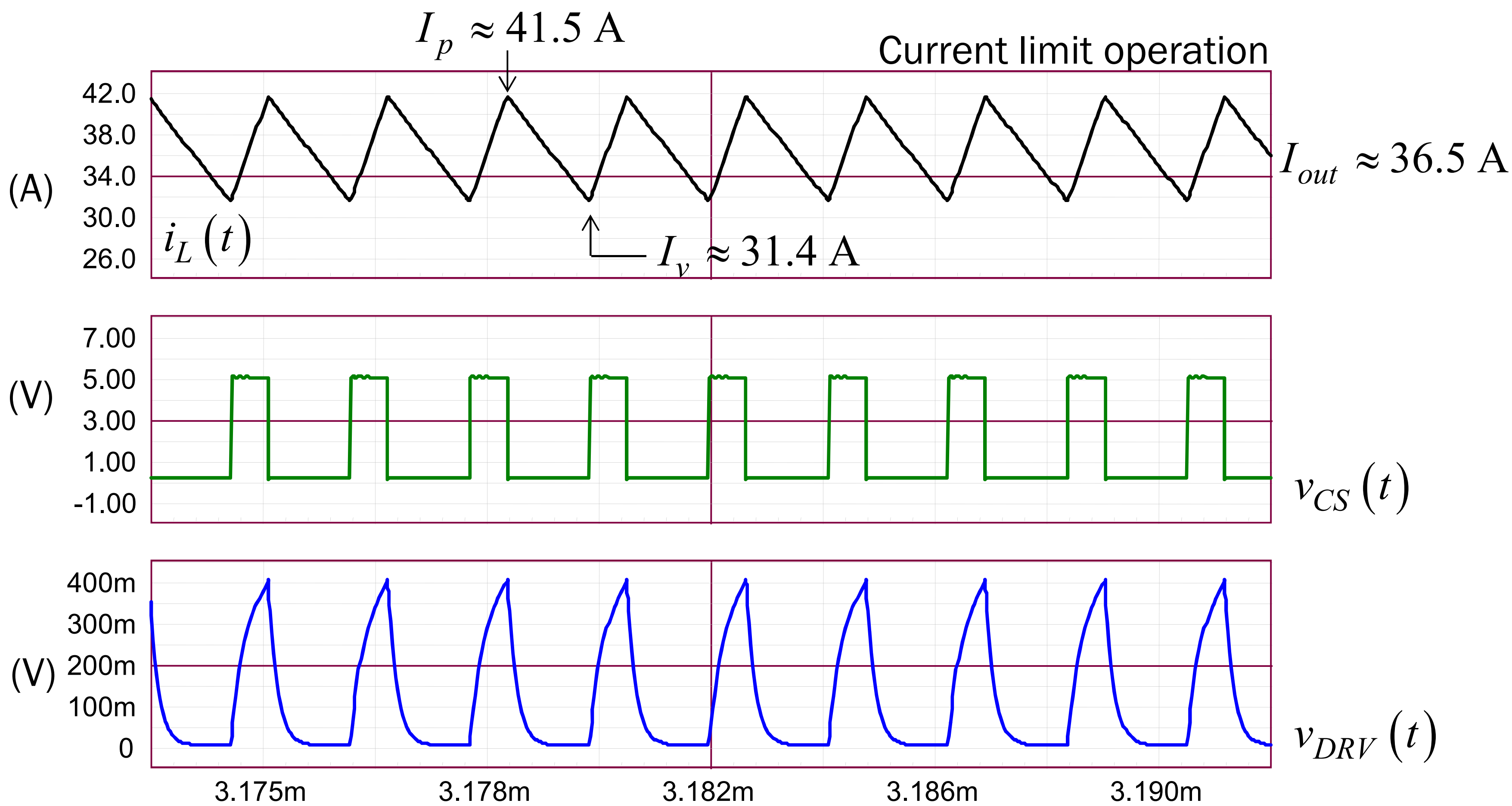
After Compensation – t_p = 130 ns

The large propagation delay slightly affects the peak at low line



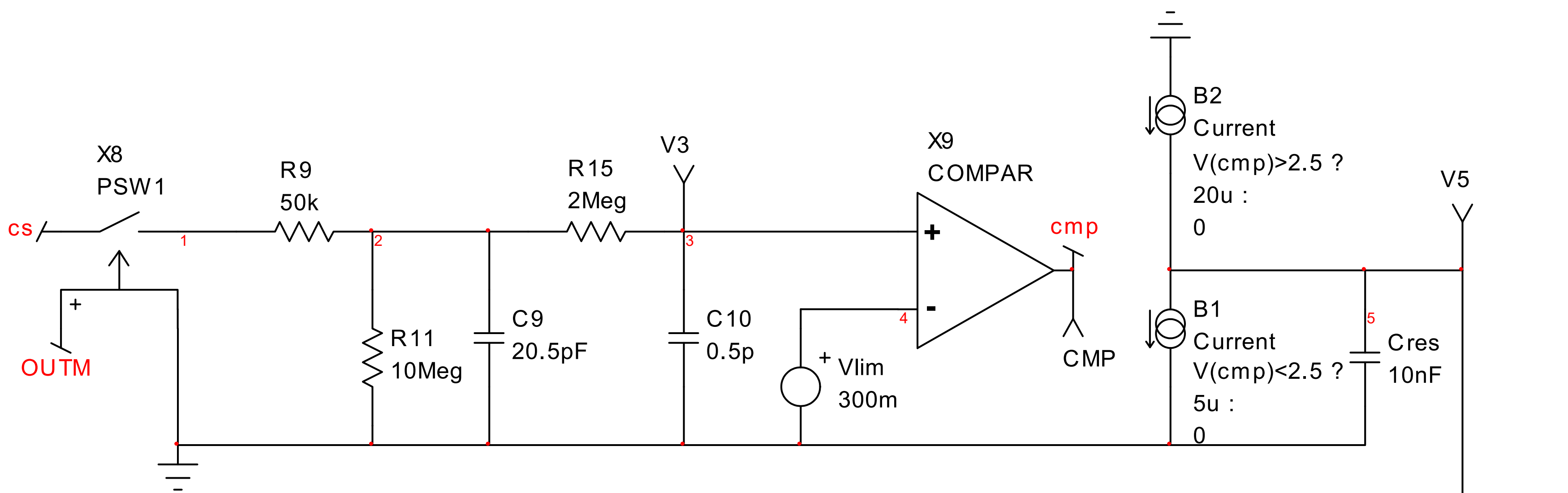
After Compensation – t_p = 130 ns

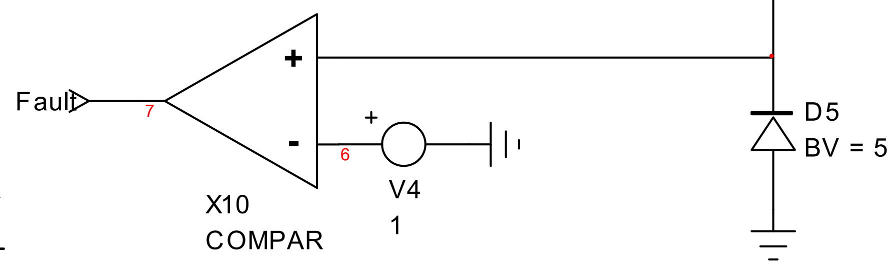
The larger propagation delay affects the peak at high line

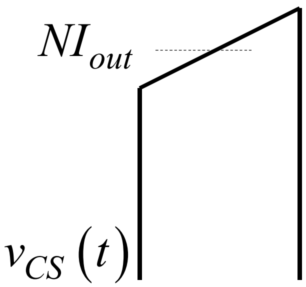


Protection Feature of NCP1565/66

NCP1565/66 include an average output current calculation in the primary side:







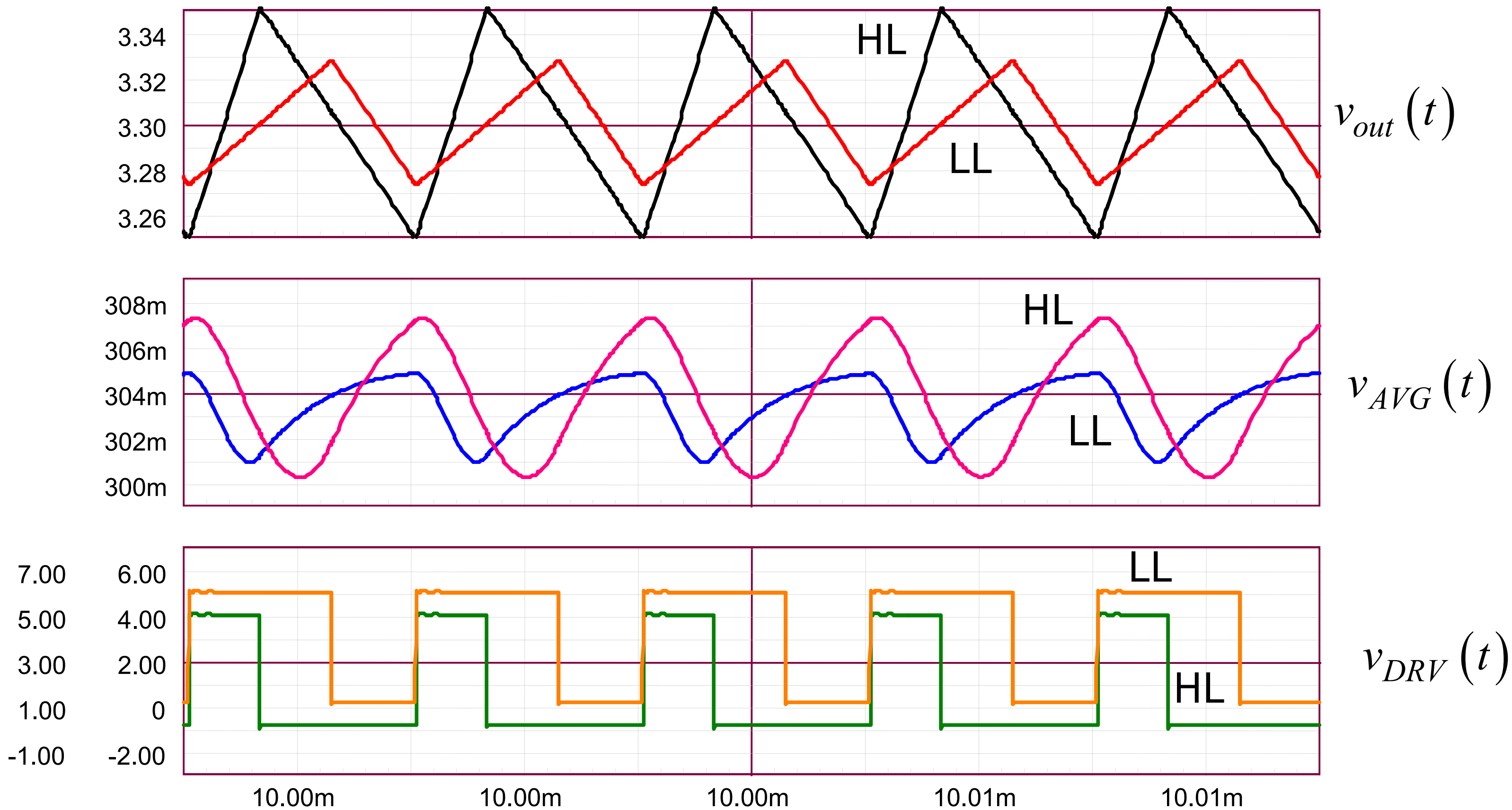
$$I_{out,\max} = \frac{300\ \text{mV}}{N \cdot R_{sense}}$$

$$I_{out,\max} = \frac{N_{CT} \cdot 300\ \text{mV}}{N \cdot R_b}$$

CT load

Waveforms at Low and High Line

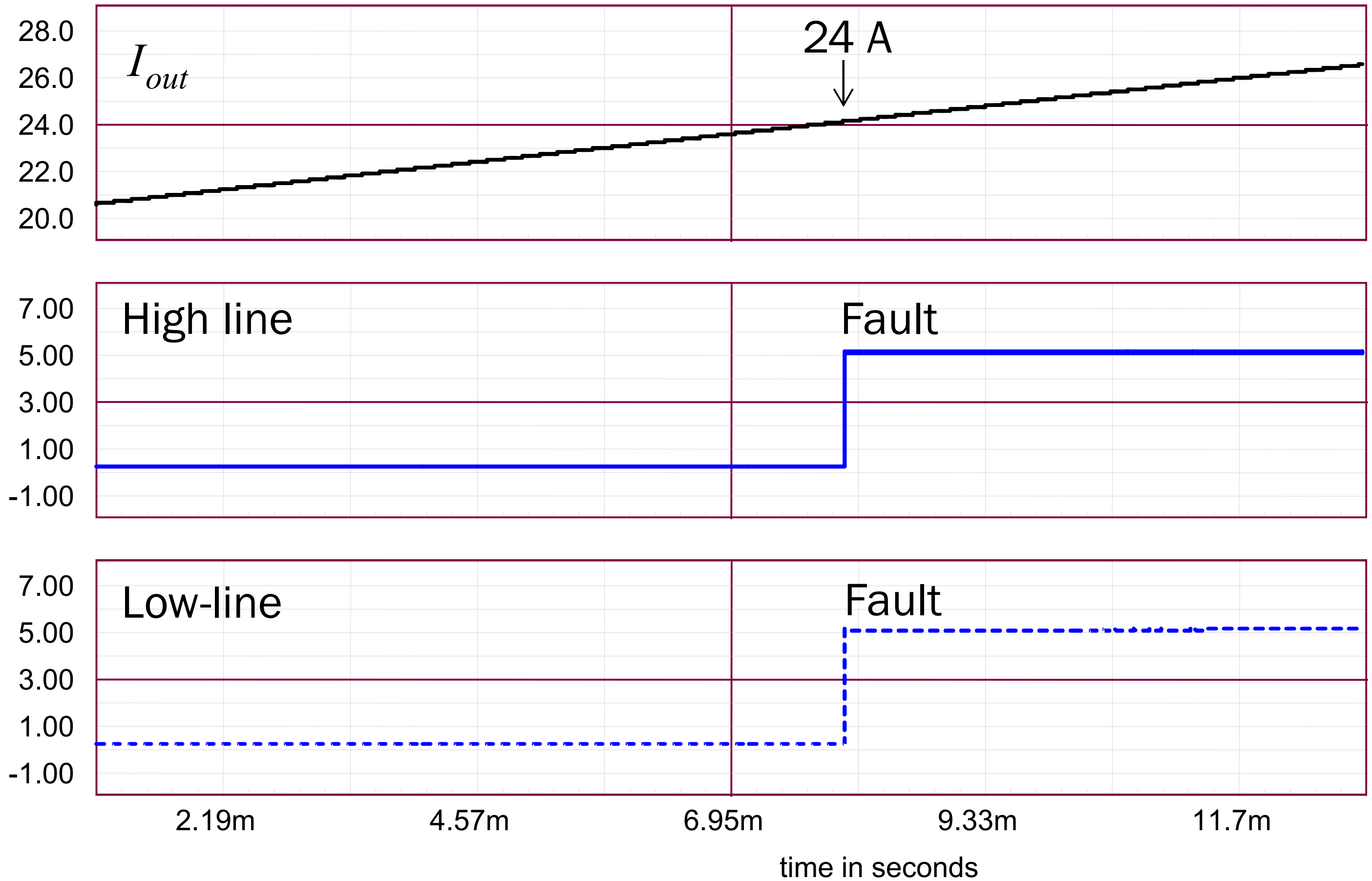
The ripple slopes slightly change with the different duty ratios at LL and HL

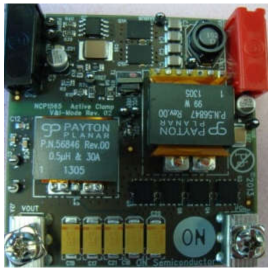


Public Information
Christophe Basso – OPP with Forward

Fault Condition

SPICE does not predict a change in the trip point between low- and high-line conditions





$$I_{out,\mathrm{LL}} = 23.46\ \mathrm{A}$$

$$I_{out,\mathrm{HL}} = 24.3\ \mathrm{A}$$

Real measurements

Conclusion

The overpower phenomenon is a classic in dc-dc switching converters: the power delivered at high line exceeds that delivered at low line.

In a forward converter, the reduction in the duty ratio happens when increasing the input voltage brings a decrease of the output inductor valley current. In this mode, the peak remains more or less constant in current-limit mode (slight overshoot in high line due to propagation delay). The average inductor current therefore reduces in high line while it can be larger in low line considering a short t_{off}.

For controllers exhibiting a fast propagation delay, it is very likely that the maximum output current at low line be larger than that of high line. In this case, a small capacitor can purposely degrade the propagation delay and both maximum HL and LL currents match. With slower controllers where $I_{out,HL} < I_{out,LL}$, it is possible to slightly offset the CS pin at high line as in the flyback case.

Thank you to Patrick Wang (Taipei) for having brought this problem to my attention. I have also appreciated technical exchanges with Joël Turchi (Toulouse).