Current and Flux Balancing for the Dual Active Bridge (DAB) Converter

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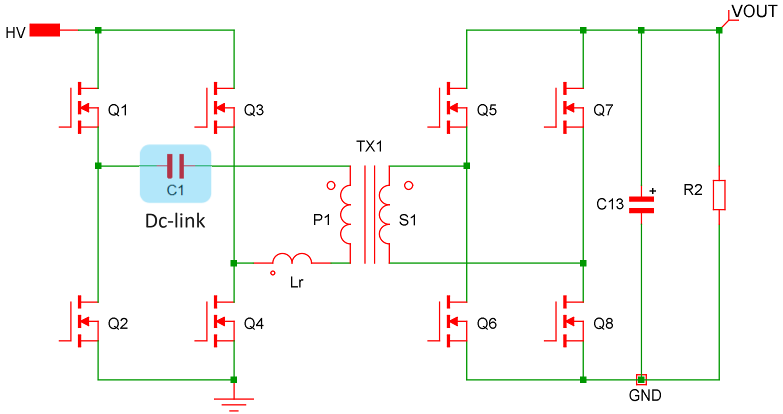
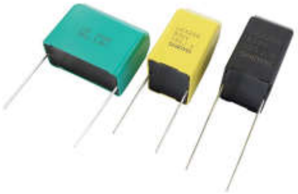
Agenda

- Why Flux Balancing?
- Adopted Principle
- Stabilizing the Loops
- Transient Analyses

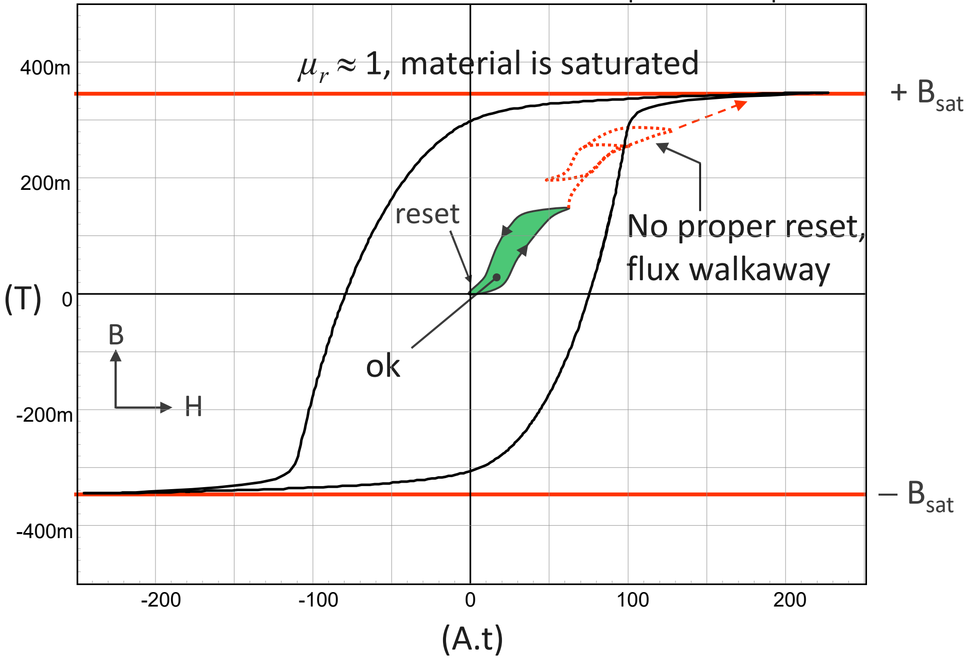
The Need to Demagnetize

- Core losses are linked to the magnetizing current and associated ΔB in the material
- Dc bias shifts the operating point and can cause saturation with catastrophic failure
- A dc-block capacitor is a solution, but it sees a large rms current and hampers cost



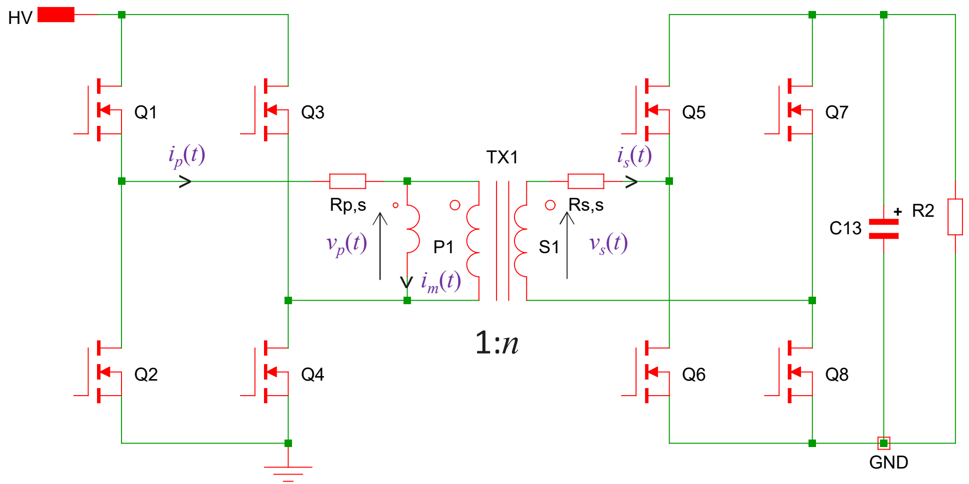


Example with 1st-quadrant



The Origin of the Drift

- Small variations in the control variables can affect the transformer volt-seconds:
  - ✓ Semiconductor forward voltage drops move with temperature
  - ✓ Insufficient pulse width modulator resolution can cause severe mismatches
  - ✓ Gate driving signal delays affect the effective on- and off-time durations



- The primary current i_p is made of the magnetizing current i_m plus the reflected output current:

$$i_m(t) = i_p(t) - n \cdot i_s(t)$$

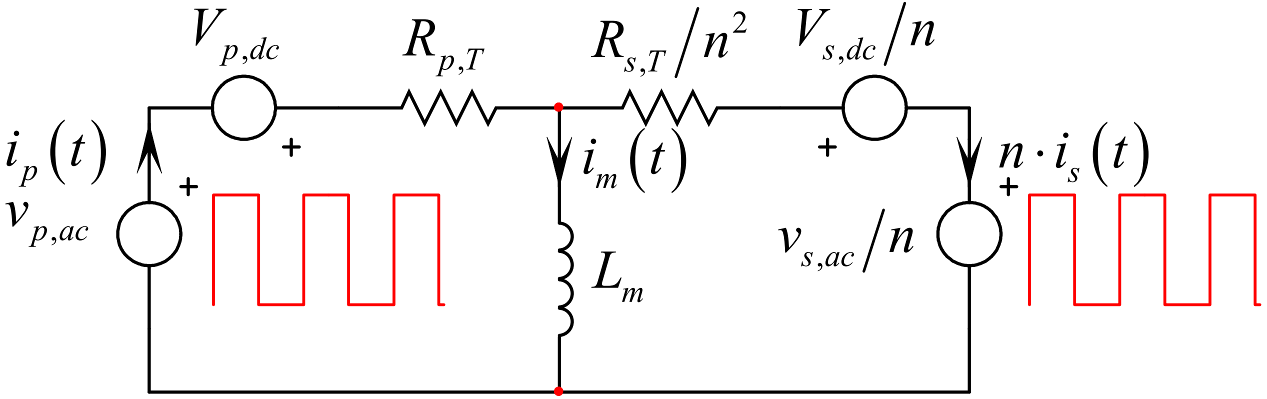
- It is possible to lump all ohmic drops into equivalent resistances in series with the primary and secondary:

$$I_{m,dc} = I_{p,dc} - n \cdot I_{s,dc} = \frac{V_{p,dc}}{R_{p,T}} - n\frac{V_{s,dc}}{R_{s,T}}$$

G. Ortiz et al., *Flux Balancing of Isolation Transformers and Application of "The Magnetic Ear" for Closed-Loop Volt–Second Compensation*, *IEEE Transactions*, vol. 29, no. 8, Aug. 2014

Modeling the Drift

- The dc magnetic flux density depends on the winding and the core
- It is limited by the equivalent series resistances $R_{p,T}$ and $R_{s,T}$
- ✓ These resistances are extremely low for the best possible efficiency

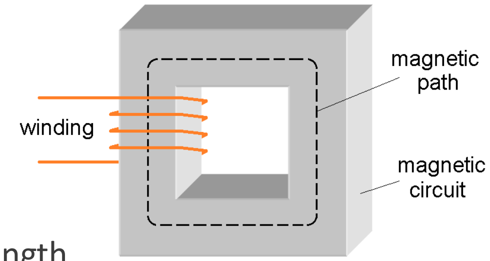


$$H = \frac{NI}{l_m} \qquad B = \mu_0 \mu_r H$$

$$B = \frac{N_p \cdot I_{m,dc}}{l_m} \mu_0 \mu_r$$

$$B_{dc} = \left(\frac{V_{p,dc}}{R_{p,T}} - n \frac{V_{s,dc}}{R_{s,T}} \right) \cdot \frac{N_p}{l_m} \cdot \mu_0 \mu_r$$

l_m → mean magnetic path length



Assessing Transformer Flux Imbalance

- The drift can be significant in a high-power converter:

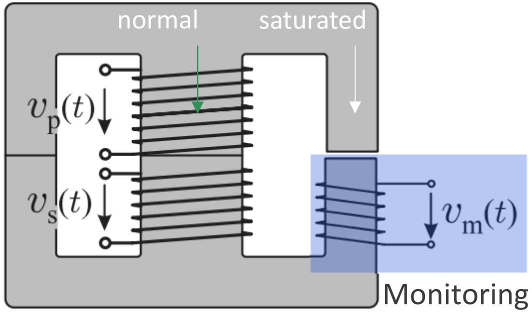
$$R_{p,T} = 1.7\ \mathrm{m\Omega} \quad F_{sw} = 20\ \mathrm{kHz} \quad P_{out} = 166\ \mathrm{kW} \quad F_{sw} = 20\ \mathrm{kHz} \quad \mu_r \approx 1950$$

- Material is N87 with a μ_r of 1950 and the error in on- off-primary duration is 0.0125%

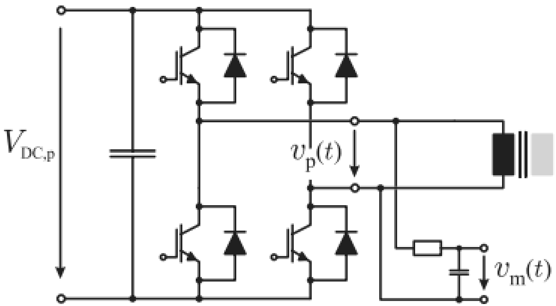
➢ This is a 2.5-ns timing error which leads to dc flux density component of B_{dc} = 50 mT

❖ Risks of saturation, nonlinear magnetizing current and higher core losses under dc bias

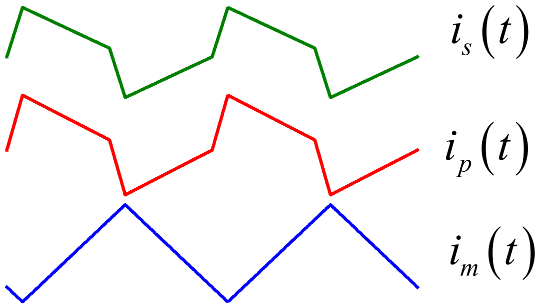
Saturation detection by parallel flux path



Dynamic flux measurement



Magnetizing current reconstruction



$$i_m(t) = i_p(t) - n \cdot i_s(t)$$

J. Muhlethaler et al., *Core Losses Under the Dc Bias Condition Based on Steinmetz Parameters*, *IEEE Transactions on Power Electronics*, vol. 27, no. 2, 2012

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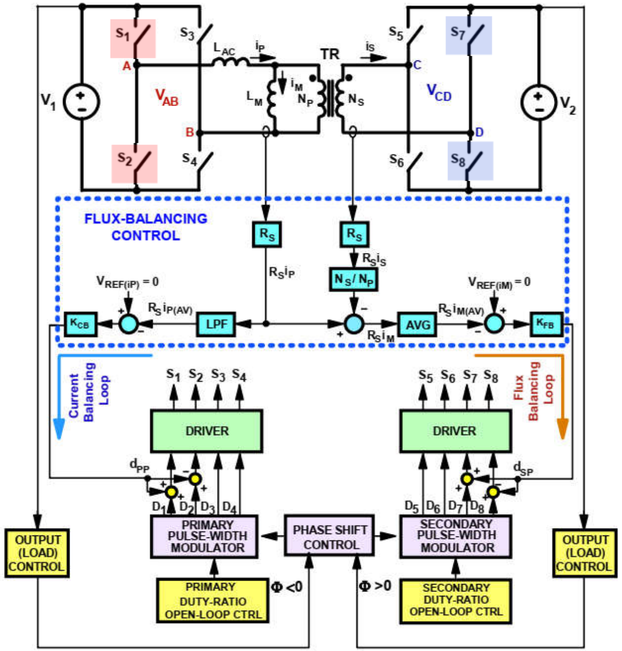
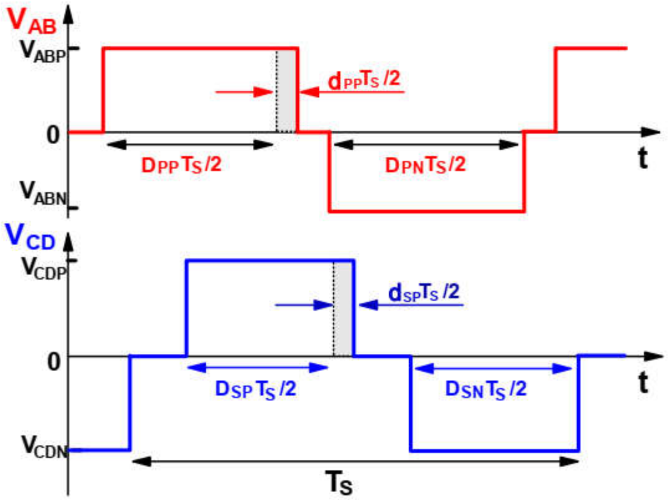
Digital Control of Currents

- Active control offers a way to cancel dc shift of magnetizing and primary currents
- Primary and secondary currents are sampled and treated via two control loops
  - One-sided modulation simplifies the control strategy



S_1-S_2 modulation

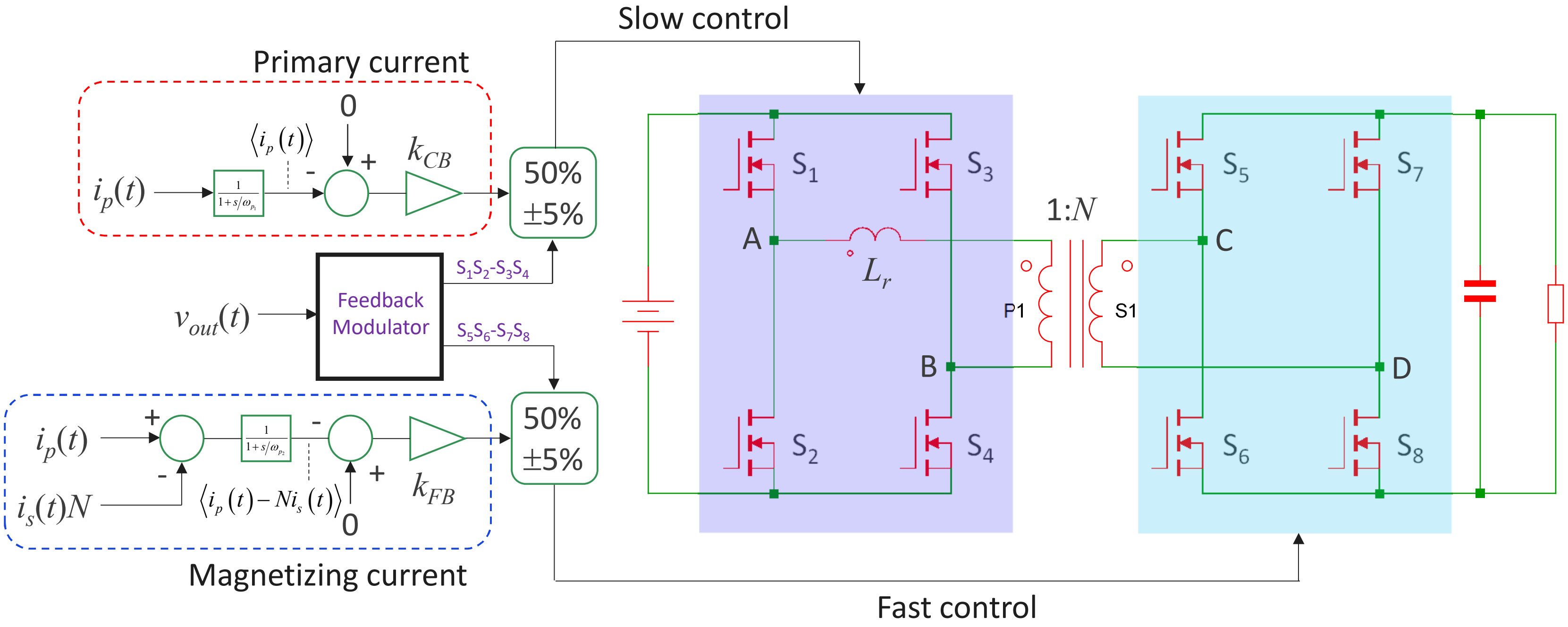
S_7-S_8 modulation



M. Jovanović et al., *Novel Transformer-Flux-Balancing Control of Dual-Active-Bridge Bidirectional Converters*, *APEC 2015*, March 2015

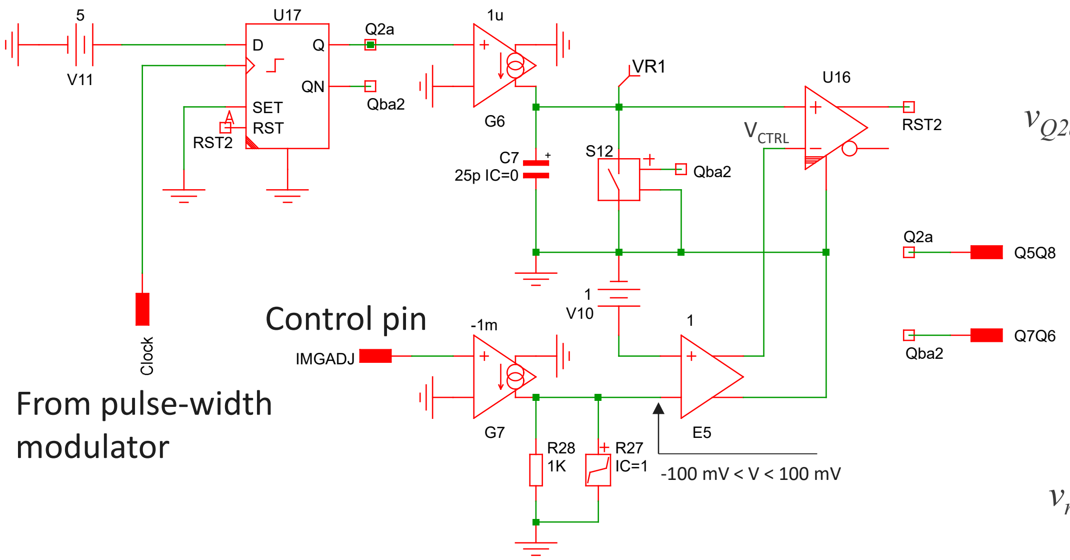
Analogue Control of Currents

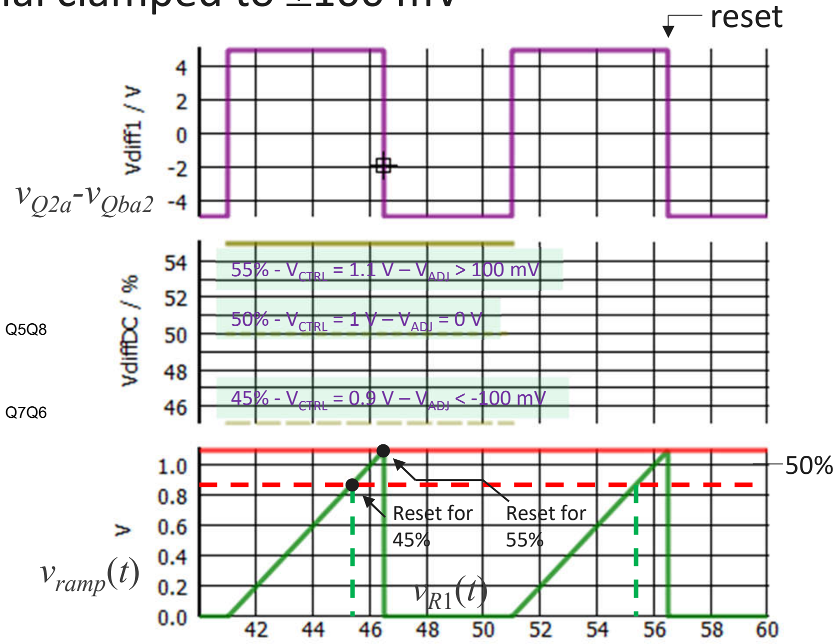
- The primary and the reconstructed magnetizing currents are averaged
- Regulation loops adjust primary- and secondary-side bridges duty ratios
  - Narrow-ranged modulation provides on-the-fly compensation



Modulating Duty Ratios

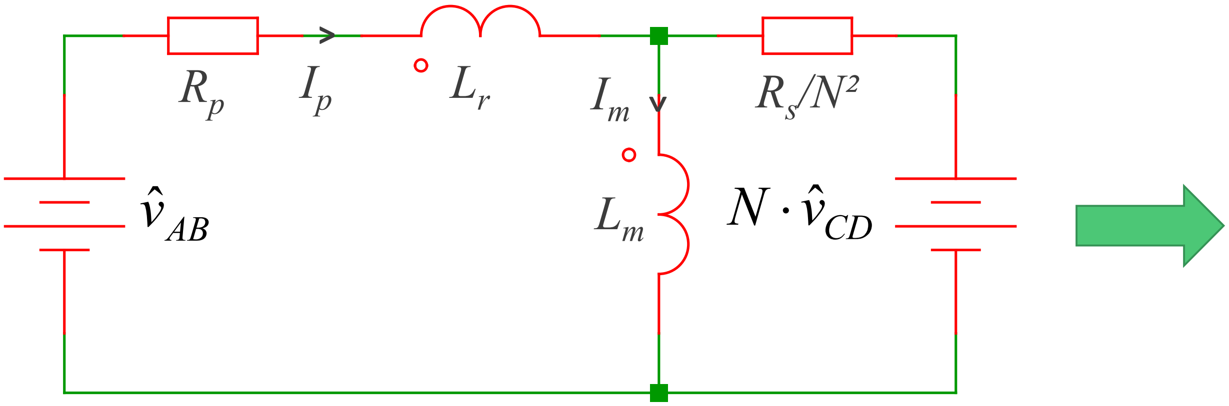
- The original control strategy implies a fixed 50% duty ratio for both bridges
- A circuit modulating around this nominal point must be designed for loop control
  - A ramp is started and peaks to 1 V at exactly $T_{sw}/2$ or 5 µs for a 100-kHz F_{sw}
  - The reset point is adjusted by the control signal clamped to ±100 mV





Modeling the Loops

- It is important to determine the transfer functions linking I_m and I_p to the duty ratios
- An equivalent small-signal circuit is necessary for stability analysis



$$H_1(s) = \frac{I_m(s)}{V_{CD}(s)}$$ Response / Stimulus

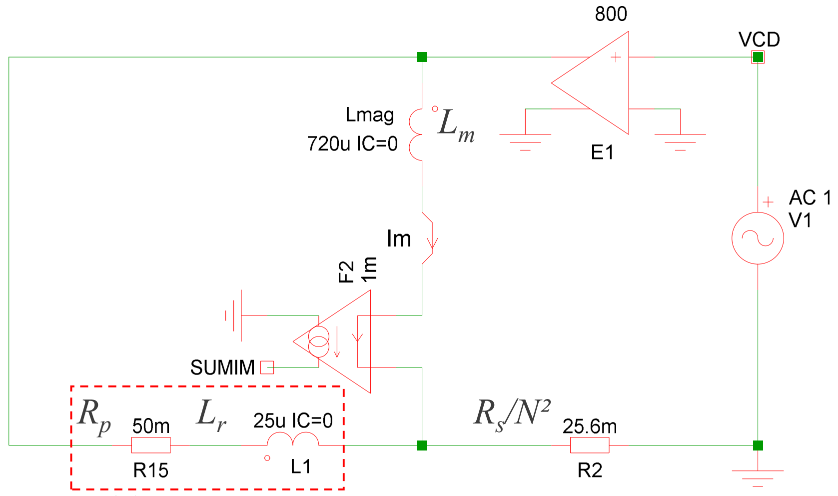
$$H_2(s) = \frac{I_p(s)}{V_{AB}(s)}$$ Response / Stimulus

✓ R_p lumps ohmic losses from primary-side power switches and magnetics

✓ R_s involves secondary-side switches and ohmic losses

Control-to-Magnetizing Current

- The slow-loop keeps source v_{AB} constant while modulating v_{CD}
  - Zero v_{AB} and replace it by a wire in the circuit: determine time constants using FACTs



$$Z_1(s) = R_p + sL_r$$

$$H_0 = \frac{V_{out}}{1\,\mathrm{V}\cdot N}\cdot\frac{N^2}{R_s} \qquad \tau_1 = \frac{L_m}{\frac{R_s}{N^2}\,||\,R_p} \qquad \tau_2 = \frac{L_r}{R_p}$$

$$\tau_1\tau_2^1 = \frac{L_m}{\frac{R_s}{N^2}\,||\,R_p}\,\frac{L_r}{\frac{R_s}{N^2}+R_p}$$

$$Z_1(s) = R_p + sL_r = 0$$

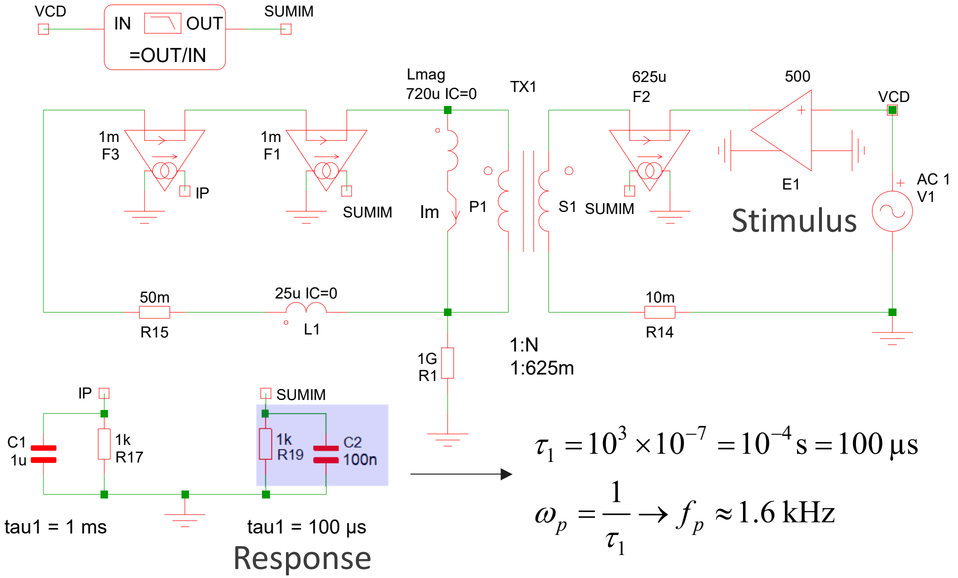
$$\rightarrow \omega_z = \frac{R_p}{L_r}$$

$$H_1(s) = \frac{V_{out}}{1\,\mathrm{V}}\frac{N}{R_s}\frac{1+s\frac{L_r}{R_p}}{1+s\left(\frac{L_m}{\frac{R_s}{N^2}\,||\,R_p}+\frac{L_r}{R_p}\right)+s^2\frac{L_m}{\frac{R_s}{N^2}\,||\,R_p}\frac{L_r}{\frac{R_s}{N^2}+R_p}} = H_0\frac{1+\frac{s}{\omega_z}}{1+\frac{s}{\omega_0 Q}+\left(\frac{s}{\omega_0}\right)^2}$$

$$\omega_0 = \frac{1}{\sqrt{b_2}} \qquad Q = \frac{\sqrt{b_2}}{b_1}$$

Simulating the Circuit

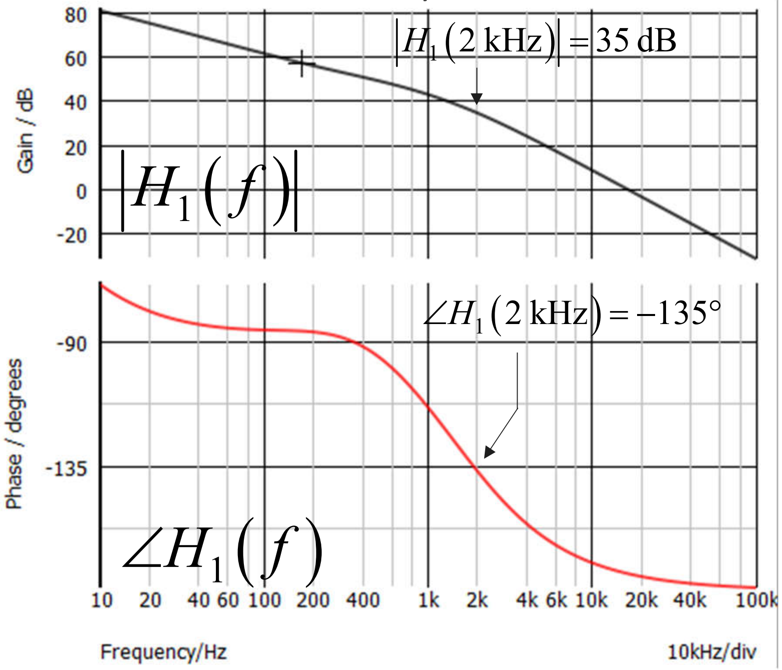
- A time constant is added to the network for averaging purposes
- This pole stresses the phase response further but does not hamper potential crossover



$$\tau_1 = 10^3 \times 10^{-7} = 10^{-4}\,\mathrm{s} = 100\,\mu\mathrm{s}$$

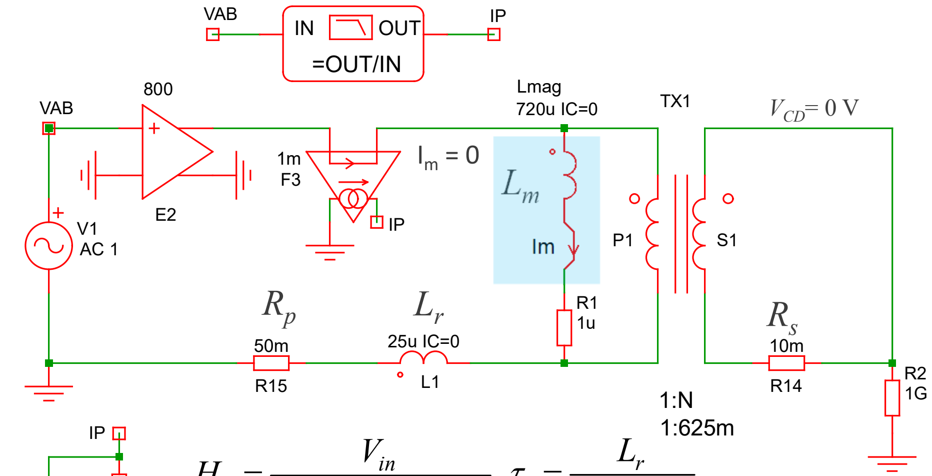
$$\omega_p = \frac{1}{\tau_1} \to f_p \approx 1.6\,\mathrm{kHz}$$

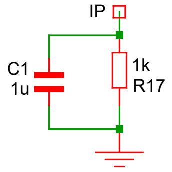
Shift the curve down by 35 dB



Control-to-Primary Current

- The fast flux-balancing loop keeps the average magnetizing current to 0 A
  - A zeroed averaged magnetizing current implies a nulled v_{CD}



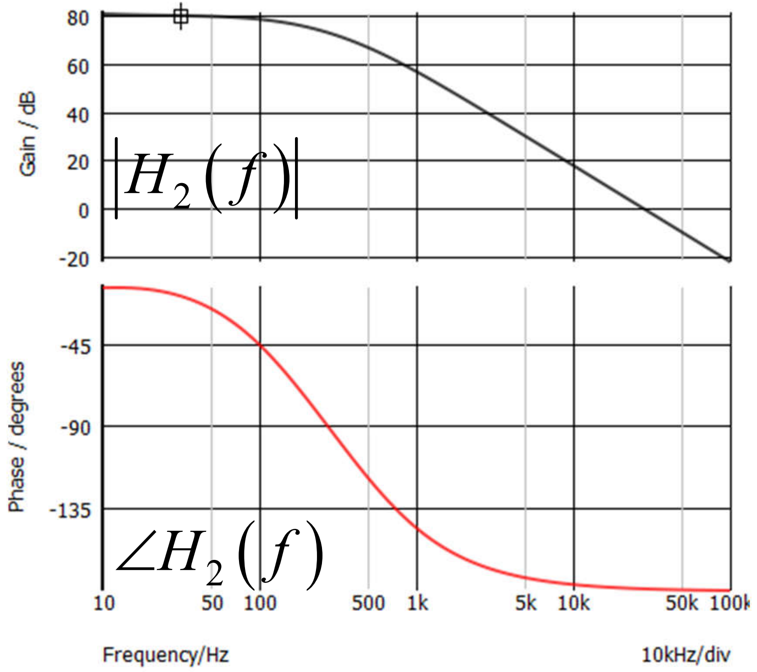


tau1 = 1 ms

$$H_0 = \frac{V_{in}}{1\,\mathrm{V}\cdot\left(R_p + \dfrac{R_s}{N^2}\right)} \qquad \tau_1 = \frac{L_r}{\dfrac{R_s}{N^2} + R_p}$$

$$\omega_{p_1} = \frac{R_s/N^2 + R_p}{L_r}$$

$$H_2(s) = H_0 \frac{1}{\left(1 + \dfrac{s}{\omega_{p_1}}\right)\left(1 + \dfrac{s}{\omega_{p_2}}\right)} \qquad \omega_{p_2} = \frac{1}{1m}$$



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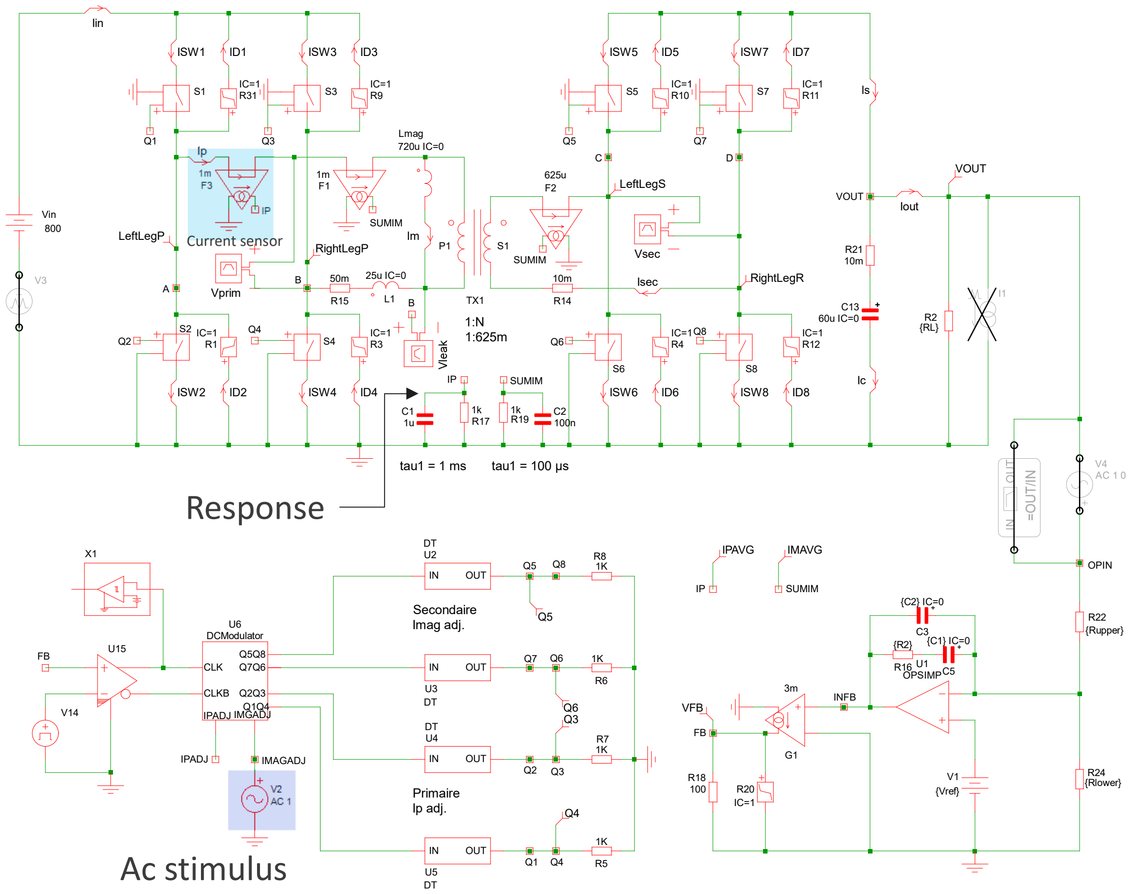
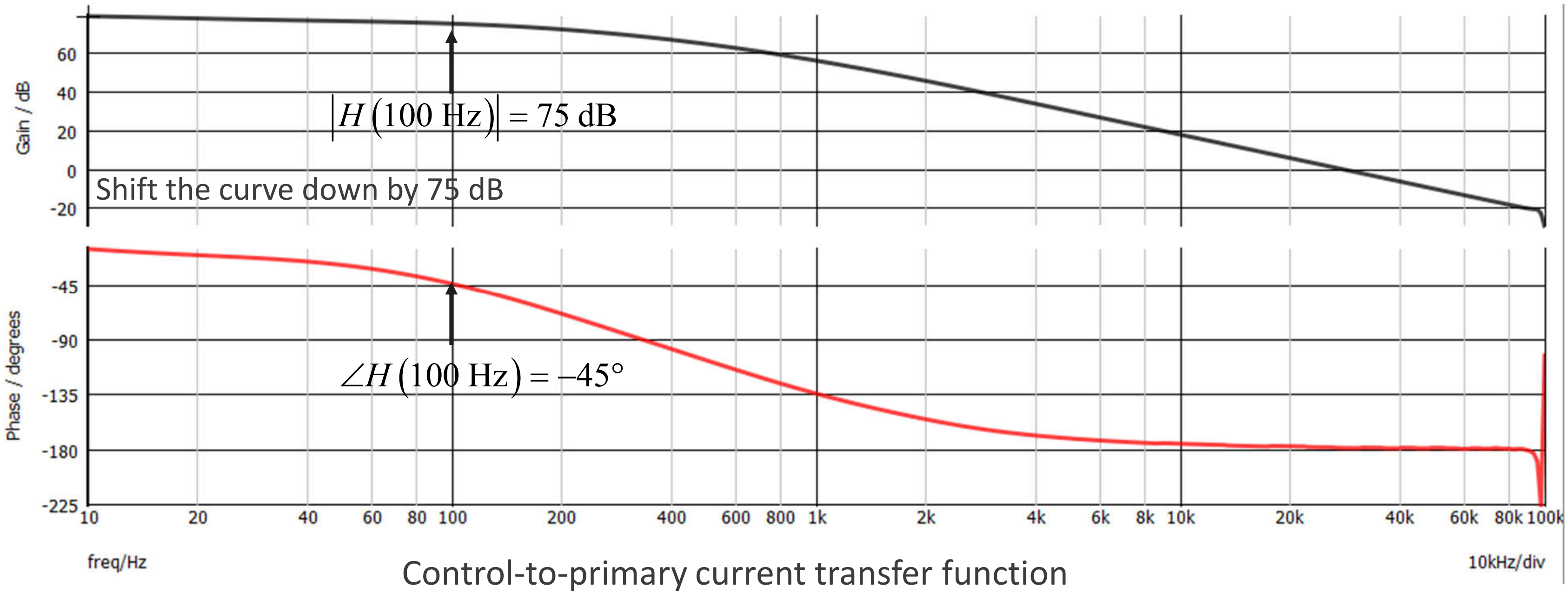
Stabilizing the Entire System Loops



- There are two control-to-output transfer functions to plot:
  - Control-to-magnetizing current
  - Control-to-primary current
- Crossover frequency of flux balancing should be high
- Crossover frequency for primary average current control is low

Primary Current Balancing Loop

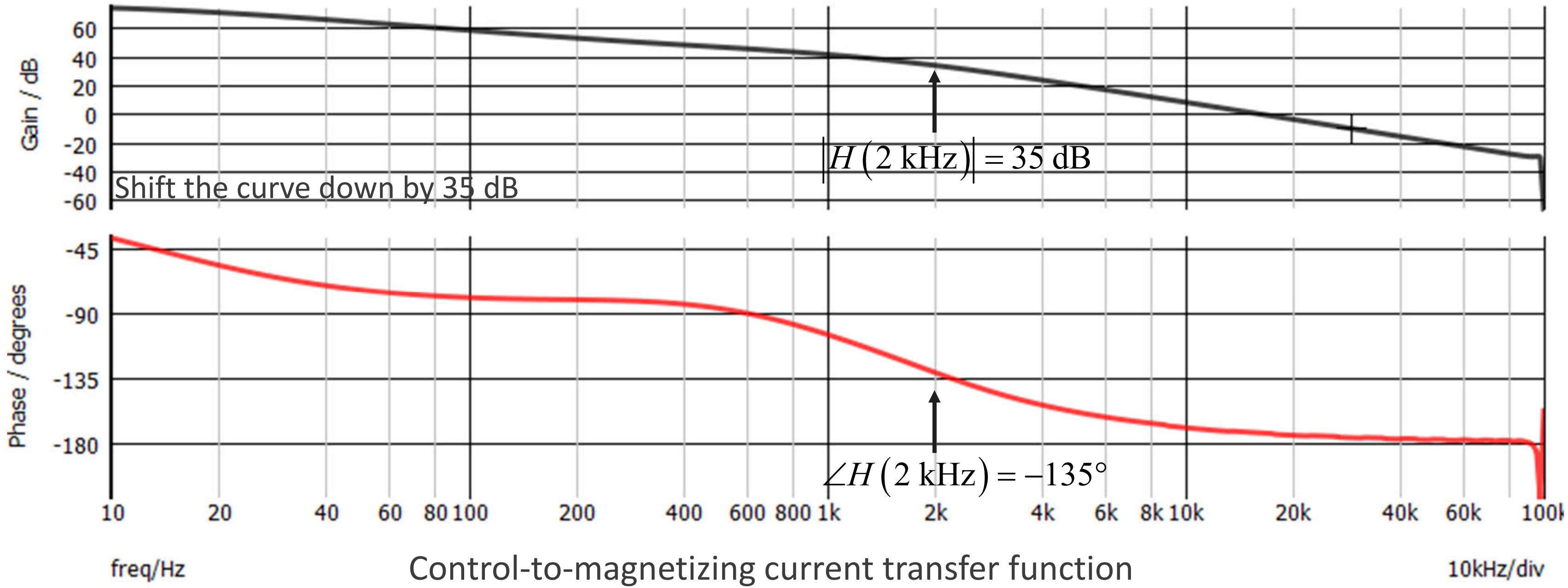
- The loop is exhibiting a high dc gain and a smooth phase response
- A crossover of 100 Hz will require a simple proportional 177u attenuation
- The phase margin will be 360-45-180 = 135° which is rock-solid



Control-to-primary current transfer function

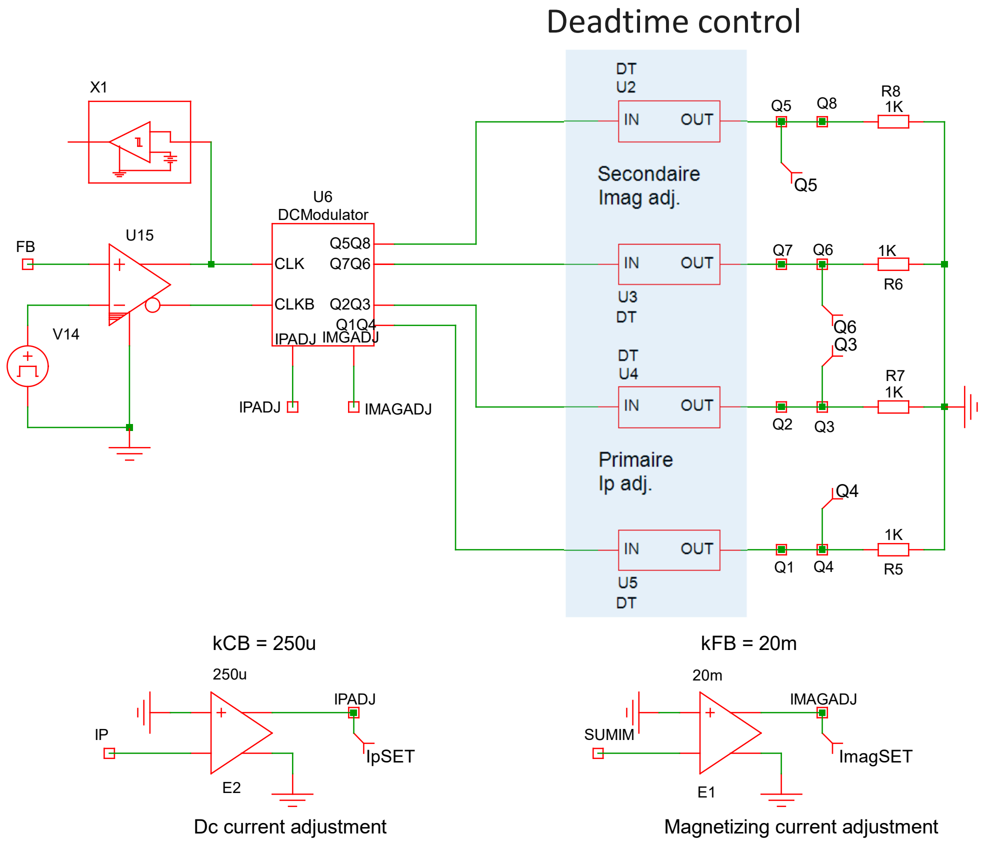
Magnetizing Current Balancing Loop

- The loop is exhibiting a high dc gain and a wide frequency response
- A crossover of 2 kHz will require a simple proportional term of 18.8m
- The phase margin will be 360-135-180 = 45° which is acceptable for this example



Control-to-magnetizing current transfer function

Closing the Inner Loops



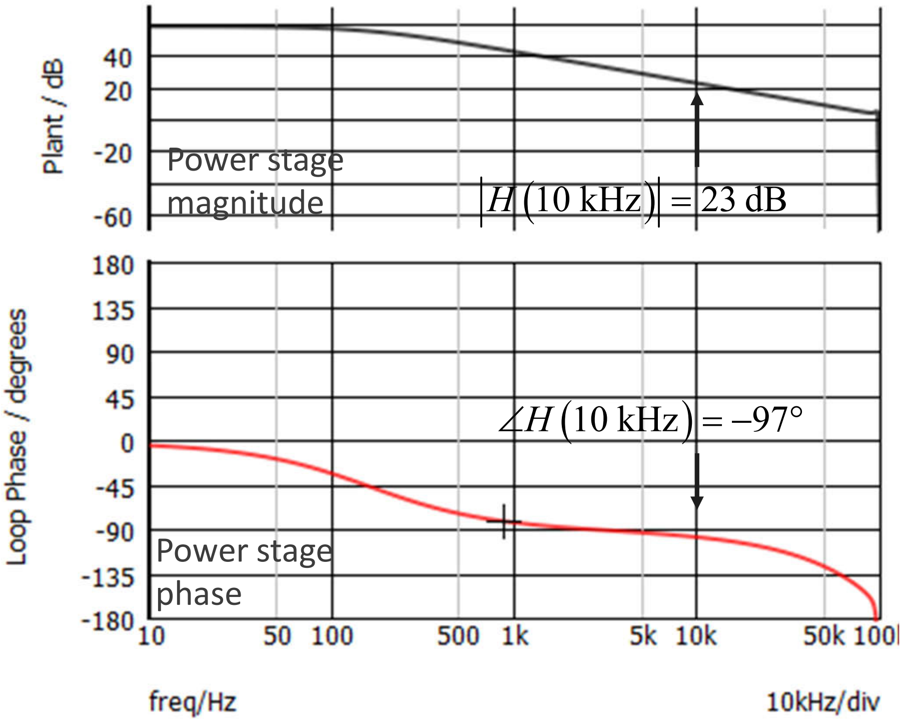
- A simple proportional gain is enough to shift down the curves
- It does not boost the phase, but margin is enough in this particular example

✓ The modulator will adjust the duty ratio for reducing magnetizing and primary currents

✓ A static error will remain despite a large inherent dc gain

Stabilizing the Main Loop

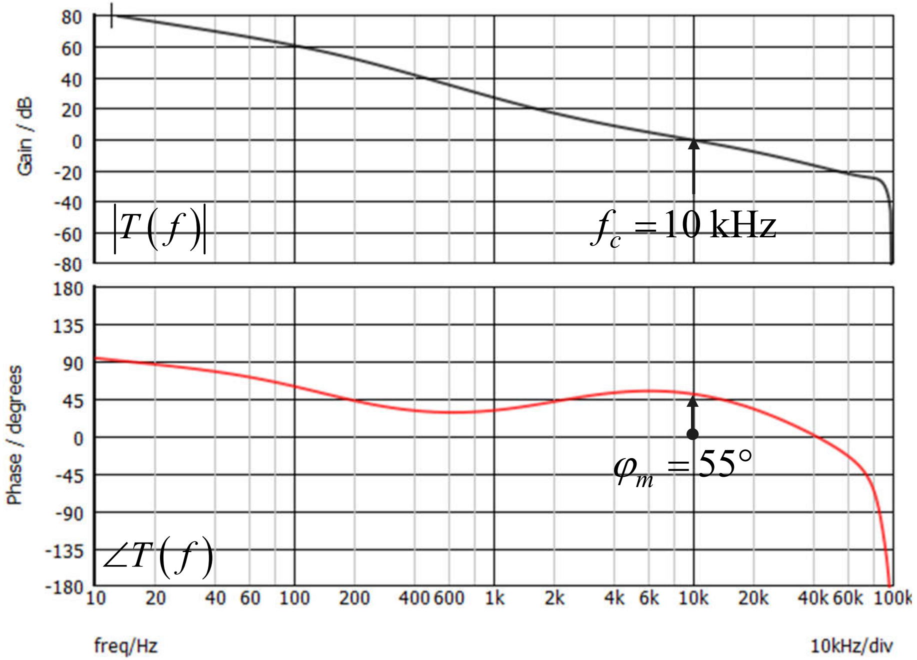
- The main loop can be compensated for a theoretical 10-kHz crossover frequency
- The compensation process is automated with a dedicated macro



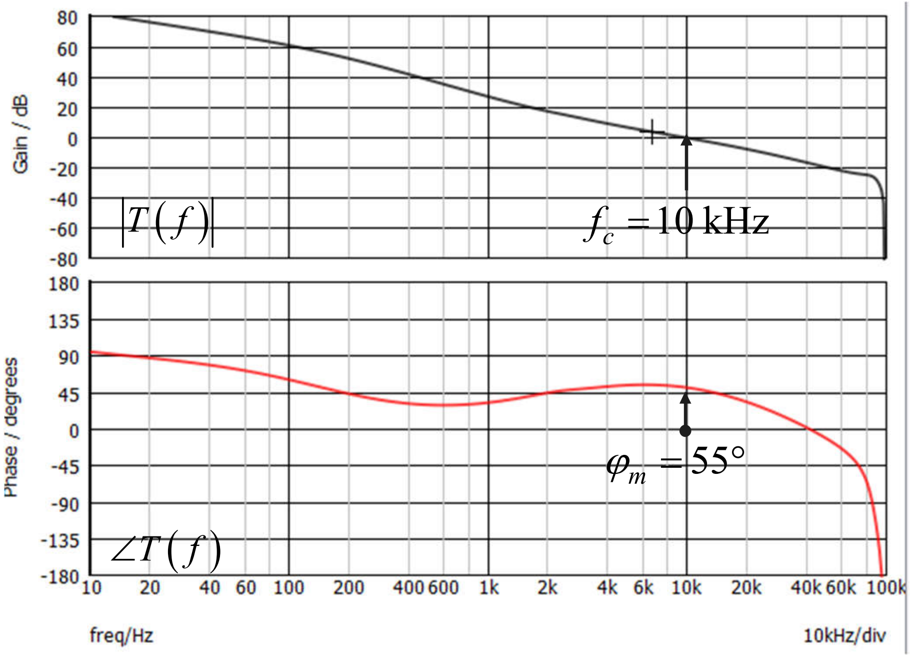

```
.VAR Gfc=23 * magnitude at crossover *
.VAR PS=-96 * phase lag at crossover *
*
* Enter Design Goals Information Here *
*
.VAR fc=10k * targeted crossover *
.VAR PM=60 * choose phase margin at crossover *
*
* Enter the Values for Vout and Bridge Bias Current *
*
.VAR Vout=500
.VAR Pout=15k
.VAR RL={Vout^2/Pout}
*
.VAR Ibias=1m
.VAR Vref=2.5
.VAR Rlower=Vref/Ibias
.VAR Rupper=(Vout-Vref)/Ibias
*
* Do not edit the below lines *
.VAR boost=PM-PS-90
.VAR G=10^(-Gfc/20)
.VAR k=tan((boost/2+45)*pi/180)
.VAR fp=fc*k
.VAR fz=fc/k
.VAR C2=1/(2*pi*fc*G*k*Rupper)
.VAR C1=C2*(k^2-1)
.VAR R2=k/(C1*2*pi*fc)
```

Compensated Converter

- The crossover is well set to 10 kHz with the two inner loops turned off
- When these inner loops are active, the overall response is preserved



$K_{CB} = K_{FB} = 0$



$K_{CB} = 250u \quad K_{FB} = 20m$

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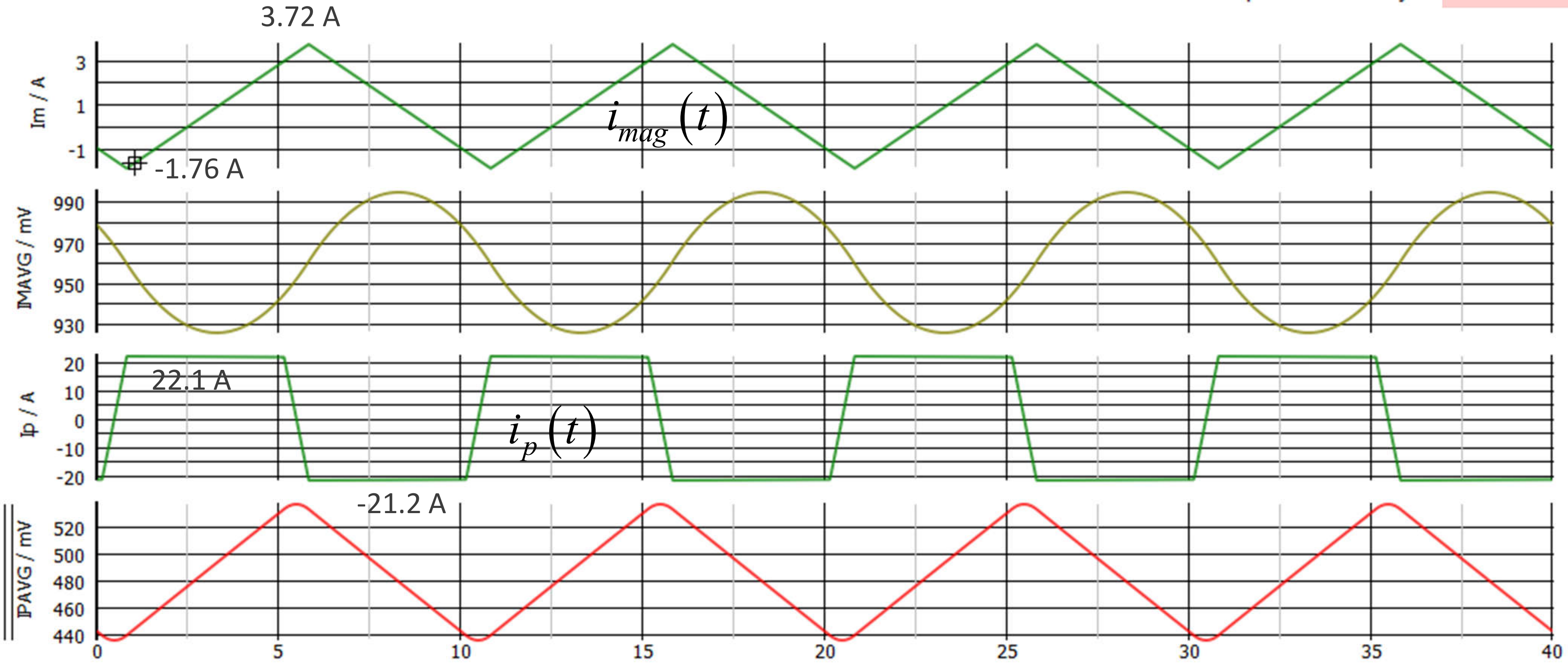
Steady-State Operations

- The two inner loops are turned off and we can observe dc shifts:

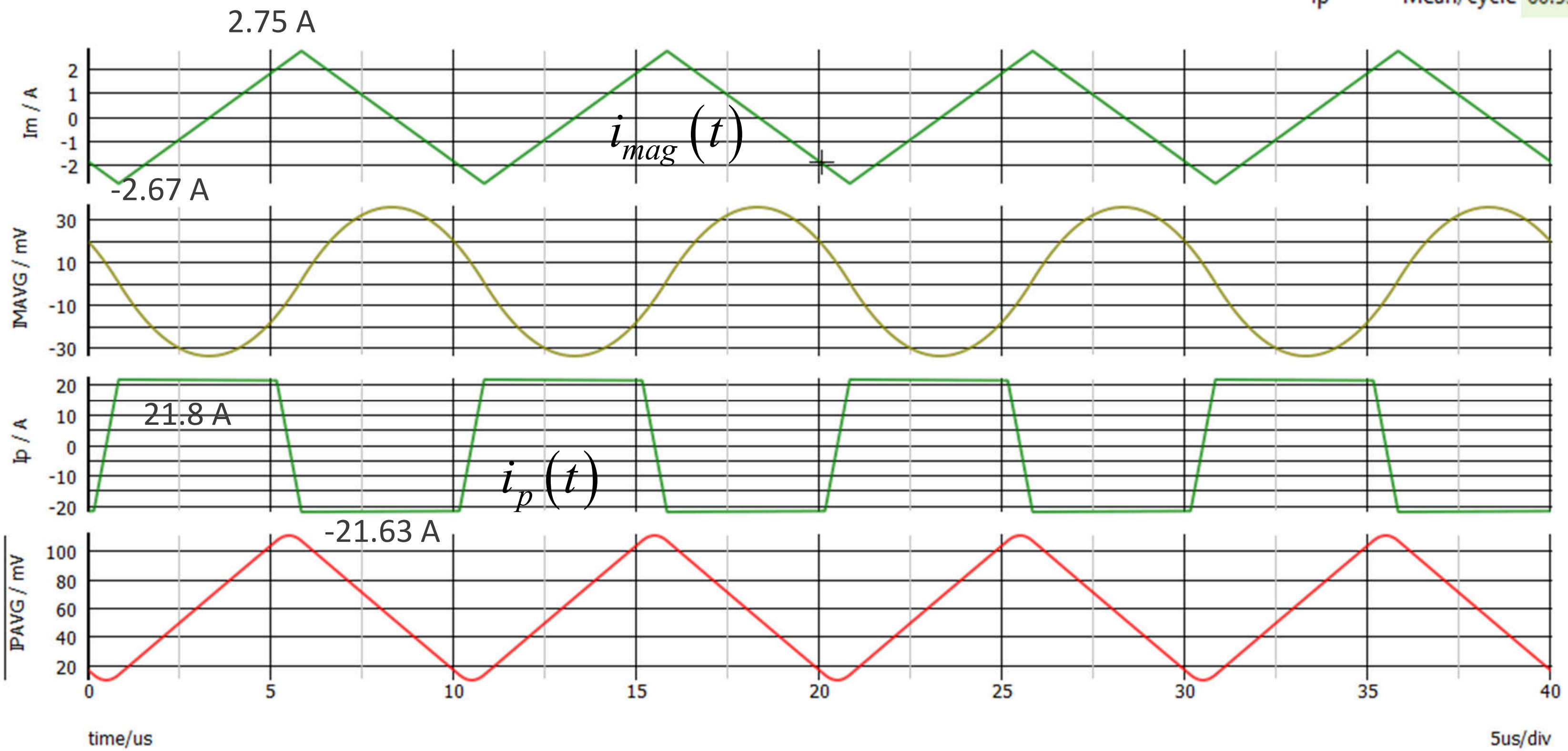
Curve label	Name	Value
Im	Mean/cycle	960.40862mA
Ip	Mean/cycle	486.37446mA



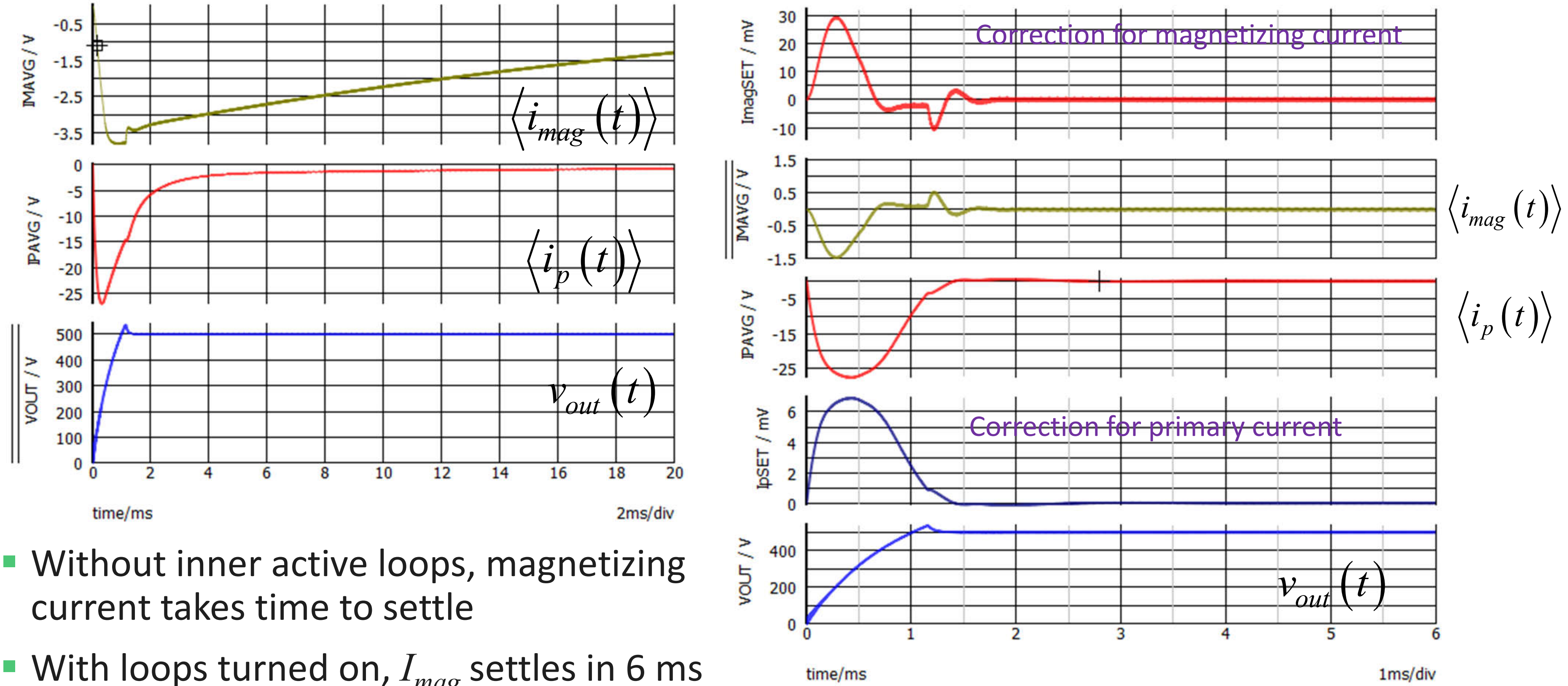
Turn the Compensation On

- The two inner loops are turned on and the dc shifts are reduced:

Curve label	Name	Value
Im	Mean/cycle	1.1401311mA
Ip	Mean/cycle	60.535187mA



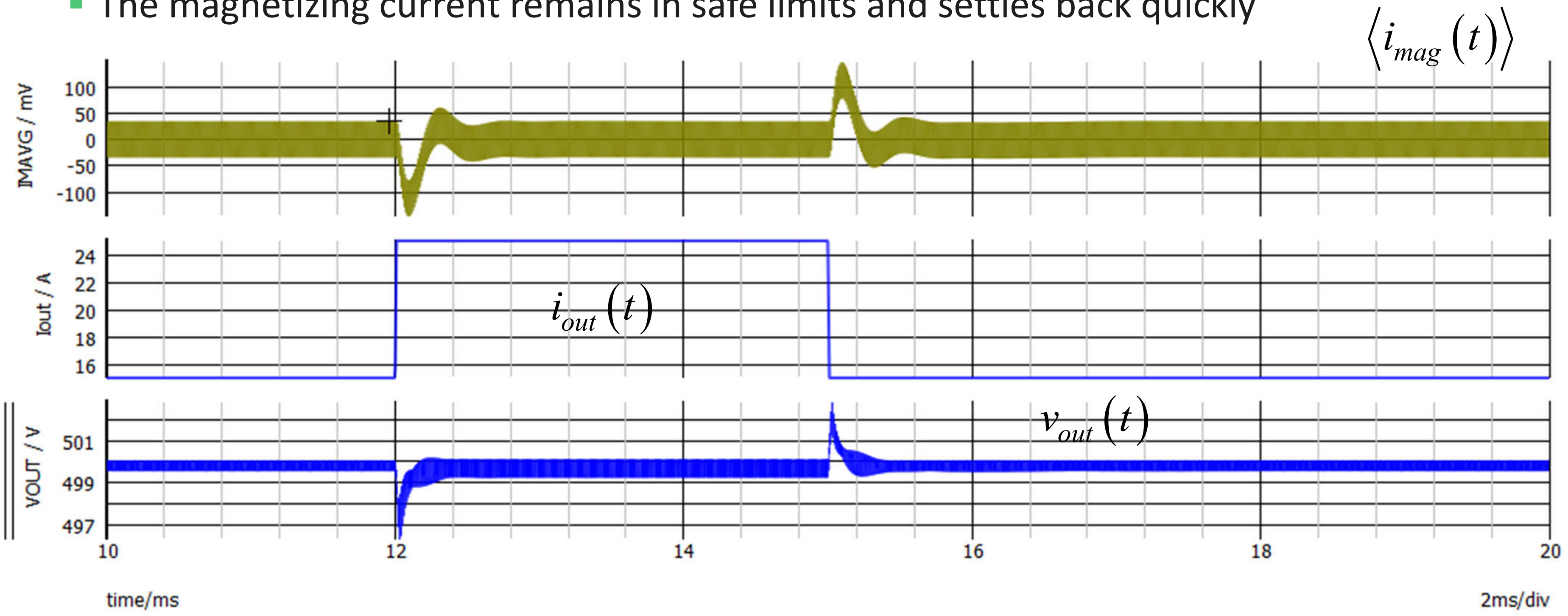
Start-up Sequence



- Without inner active loops, magnetizing current takes time to settle
- With loops turned on, I_{mag} settles in 6 ms

Transient Response – Loops are Active

- The output current is stepped from 15 to 25 A with a 1-A/µs slope
- The magnetizing current remains in safe limits and settles back quickly



Conclusion

- The transformer in a DAB converter can be the subject of dc shifts in the circulating currents
  - ✓ The shift of the magnetizing current can lead to transformer saturation
  - ✓ The dc components in the primary and secondary sides generate extra losses
  - ❖ A dc-block capacitor can certainly do the job but two are needed for a bidirectional converter
- The primary and secondary currents are used to reconstruct the magnetizing current
- Dedicated loops – fast and slow – respectively deal with flux balancing and dc shift reduction
- The compensation of the loops is simple and done via a single proportional term
- A good transient response is obtained in the end and overall reliability is increased