Advantages of Voltage Mode Control with Feed Forward

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Introduction

- The concept for Voltage Feed Forward for Voltage Mode Converters has been covered in several Publications.

- Notable Example
  - Feedforward Pulse Width Modulators for Switching Power Converters, Barry Arbetter and Dragan Maksimovic, IEEE TRANSACTIONS ON POWER ELECTRONICS, MARCH 1997.
- Recent Example
  - Enhanced Dynamic Regulation in Buck Converters, MOSTAFA AMER et al, IEEE Access, January 2024.

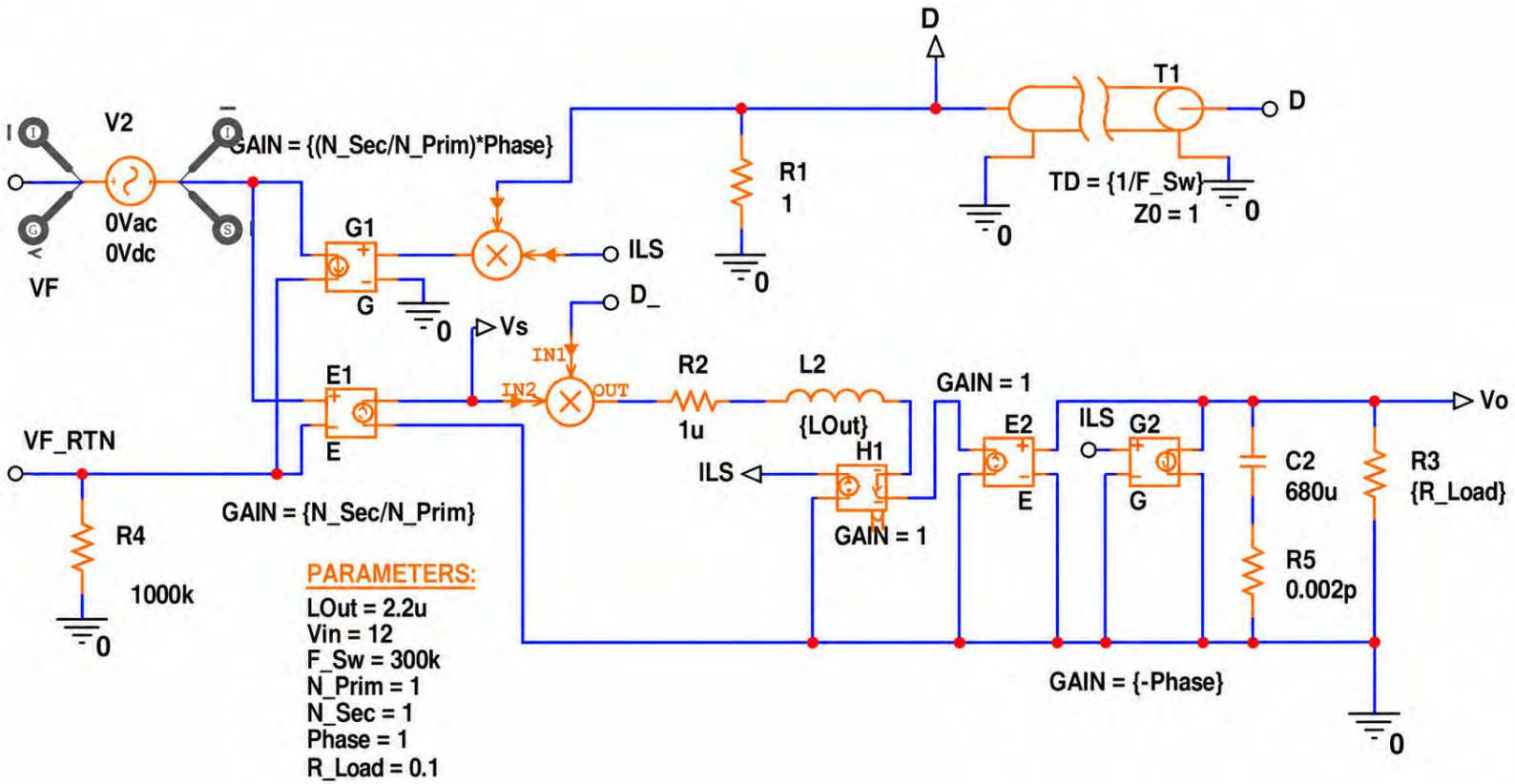
- Value of Revisiting
  - Verify Approach through Simulation.
  - Simplify Math into a digestible session.
  - Explore unique Digital Approach.

- What is there to Gain
  - Constant Input to Output Gain simplifies Control.
  - Increase margin for Impedance Matching.
  - Conserve resources – i.e. Available High-Speed Comparators.
  - Improved Invariance vs Line Voltage allows for Improved Optimization.

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Conventional Voltage Mode Buck – Example 100W 12V to 3.3V Converter

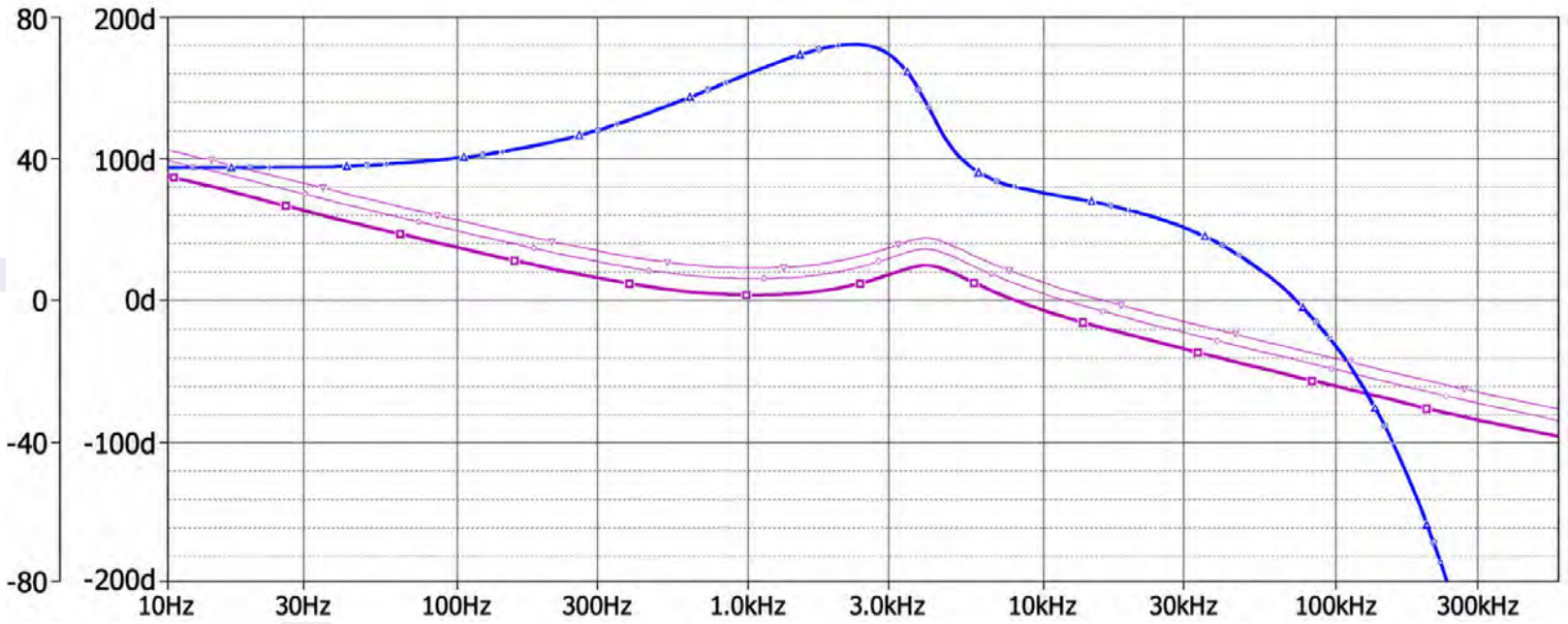
- This Model Can be used for most Buck Derived Circuits.
- Use of Parameters simplifies running Multiple models in parallel.
- If no Transformer is used, Set N_Prim and N_Sec to 1.
- Using Parameters also allows ‘parametric’ sweep.
- In this case we’ll sweep the input voltage from 6V to 16V



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Conventional Voltage Mode Buck – Example 100W 12V to 3.3V Converter

- When Input Voltage is swept from 6V to 16V, the gain increased.
- From 12V nom. To 16V, Phase margin reduces from 51° to 35°.
- From 12V nom. To 16V, Gain Margin decreases from 8 to 5db



- Why??
  - For Buck derived circuits $V_o = DV_{in}$

$D = \frac{V_{ea}}{V_m}$ where V_{ea} is error amplifier output and V_m is the P-P Sawtooth Voltage

The DC Gain of the plant, G_{Pdc}, is $\frac{V_o}{V_{ea}}$ so substituting, we get… $\boldsymbol{G_{pdc} = \frac{V_{in}}{V_m}}$

Therefore, the Final Gain is directly proportional to the input voltage.

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Introducing Voltage Feed Forward

- For Analog implementations, it is best to use an IC designed for this Application.
  - UCC28250
  - LM5036
  - These Analog circuits will increase the ramp slope proportional to $\boldsymbol{V_{in}}$.
  - If $\boldsymbol{V_{in}}$ increases by n, $\boldsymbol{V_m}$ will increase by n, thus leaving the plant gain constant.

$$\boldsymbol{G_{pdc}} = \frac{\boldsymbol{n * V_{inNominal}}}{\boldsymbol{n * V_m}}$$

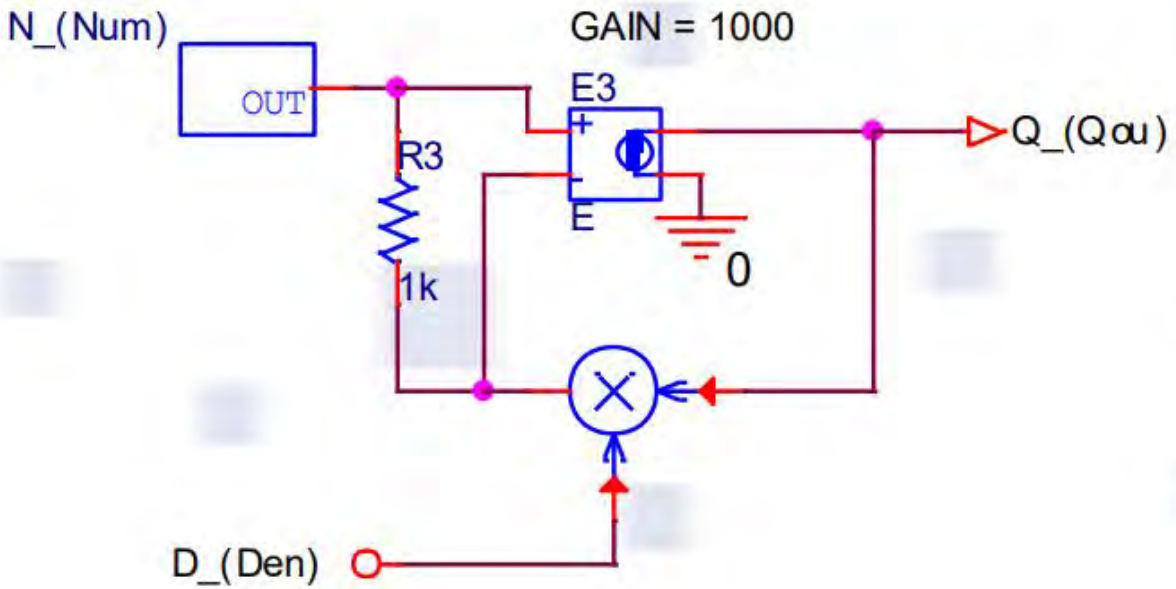
Looks like a good Analog Solution – But how can we get this into an Average model in PSPICE?? – There is no Sawtooth in the average model!

We must add a term to the plant $\frac{\boldsymbol{V_{inNominal}}}{\boldsymbol{V_{in}}}$.

But there is no real time division Library Component in SPICE.

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Emulating Division in PSPICE



Following the schematic, we can write an expression for Q

$$Q = 1000 * (N - (Q * D)$$

We can now expand the equation

$$Q = 1000N - 1000Q * D$$

Gather the Q terms

$$Q(1 + 1000D) = 1000N$$

Solve for Q

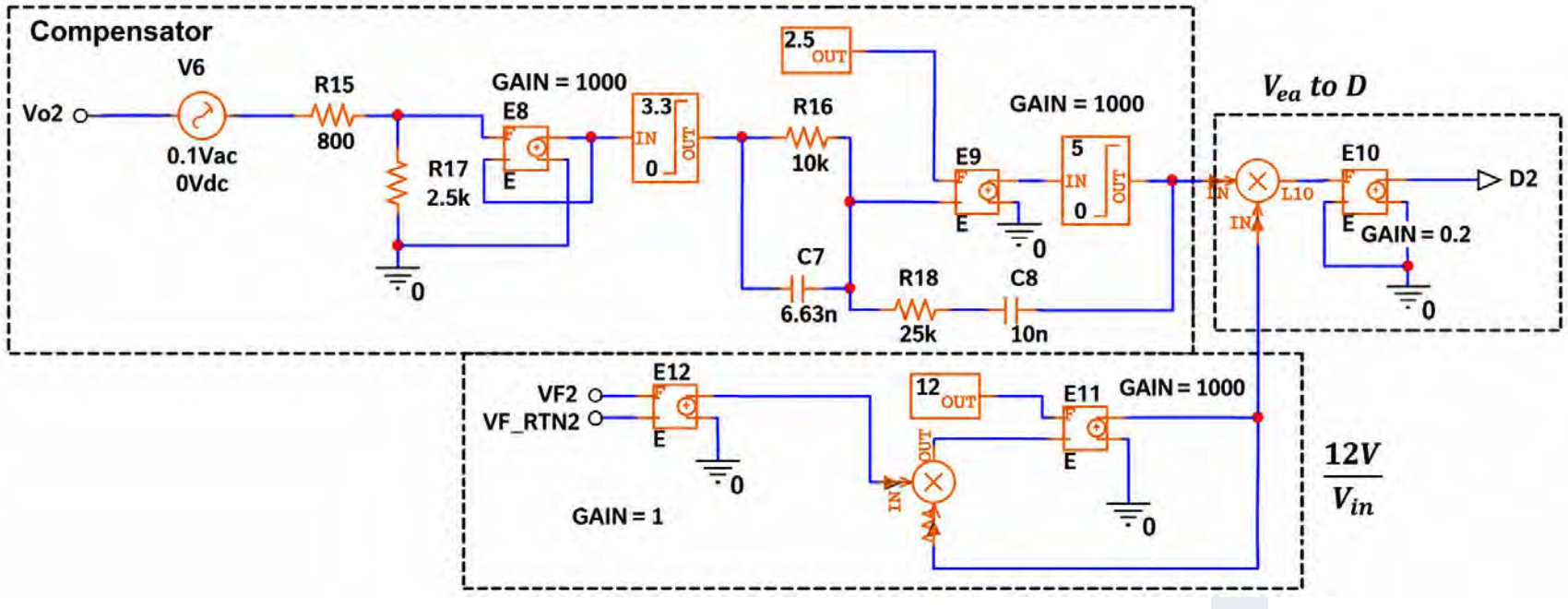
$$Q = \frac{1000N}{1 + 1000D}$$

We can see that Q is a pretty good representation of division, as long as 1000D is much greater than 1.

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Feed Forward Implemented

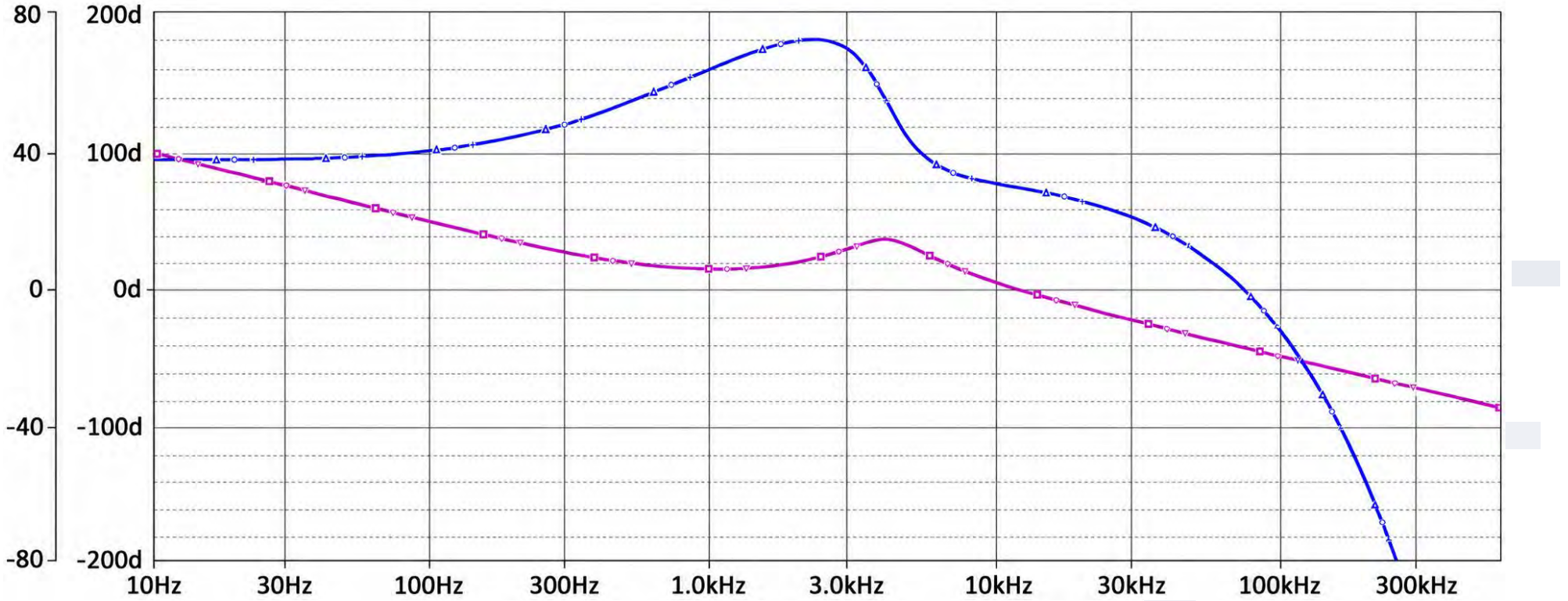
- The Compensator and the $V_{ea}\ to\ D$ elements are identical to the previous example.
- The $\frac{12V}{V_{in}}$ element is introduced.



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Feed Forward Voltage Mode Buck – Example 100W 12V to 3.3V Converter

- Again, Input voltage is swept from 6V to 16V.
- The gain does not vary with input voltage.

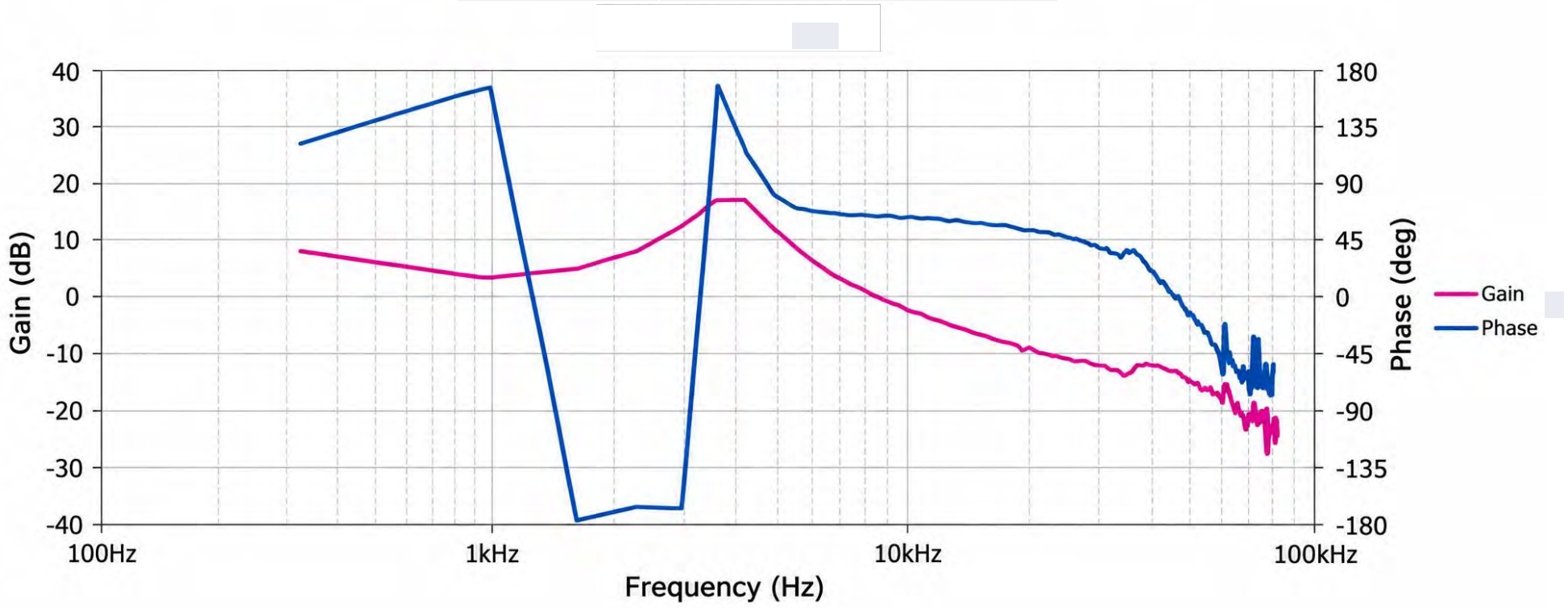


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Feed Forward Voltage Mode Buck – Example 100W 12V to 3.3V Converter

- Check against lab Data

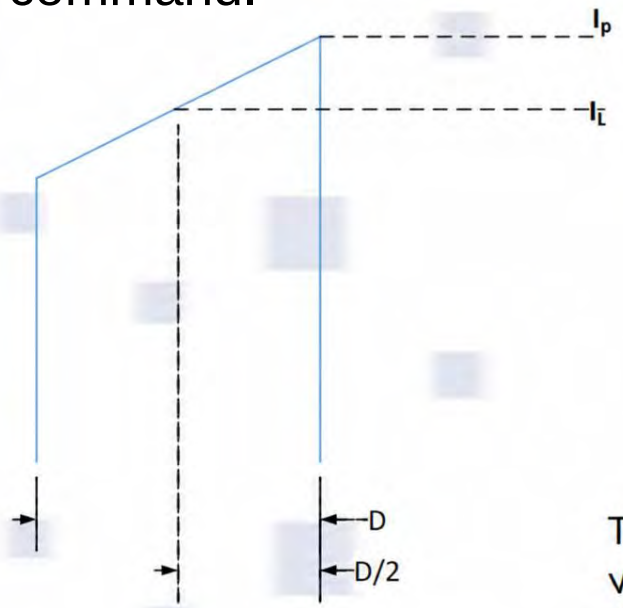
Parameter	PSpice	Lab
Gain crossover	≈11–12 kHz	≈ 9 kHz
Phase margin*	≈70–75°	≈70°
Gain margin*	≈18 dB	≈12 dB



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Compare Voltage Feed Forward to Current Mode

- For Analysis, Construct an Average Current Mode Model in Spice
- For Voltage mode, V_{ea} was multiplied by a constant to arrive at the Duty Cycle.
- In current mode, V_{ea} is a Commanded current to the modulator. The Duty Cycle is a result of the command.



The commanded Current from the controller is i_P , The resulting average current is i_L

$$i_P = i_L + \frac{v_L}{L} * \Delta T \text{ , where } \Delta T = \frac{d}{2} * \frac{1}{F_{SW}}$$

Solving for d yields…

$$d = (i_P - i_L) * \frac{2F_{SW}L}{v_L}$$

This is a fairly simple equation, except for one problem… The inductor voltage varies and requires SPICE to perform real-time division. There is no library part in SPICE, so we must introduce a method.

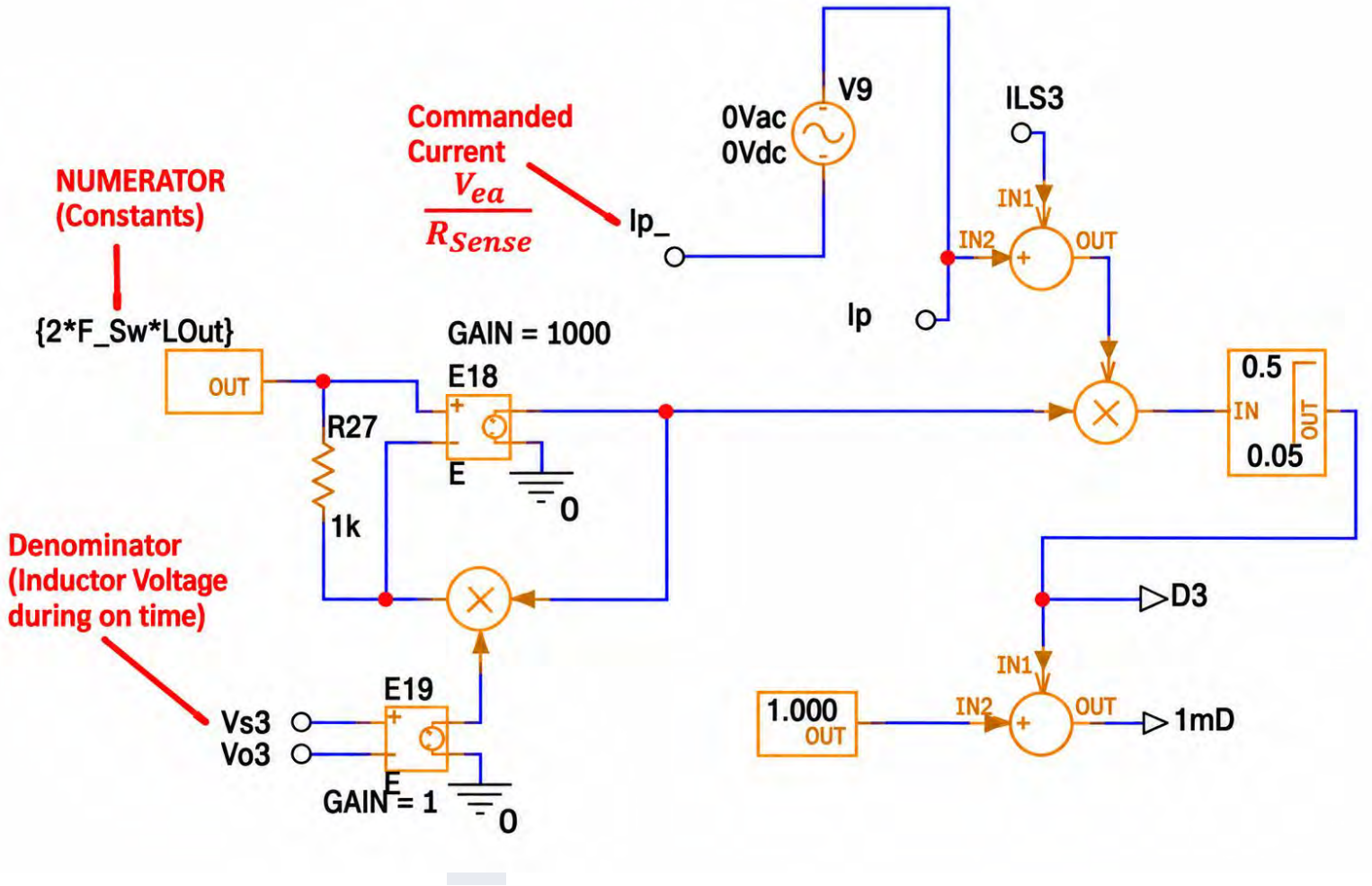
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Constructing an Average Current Mode Model in SPICE

- Equation

$$d = (i_P - i_L) * \frac{2F_{SW}L}{v_L}$$

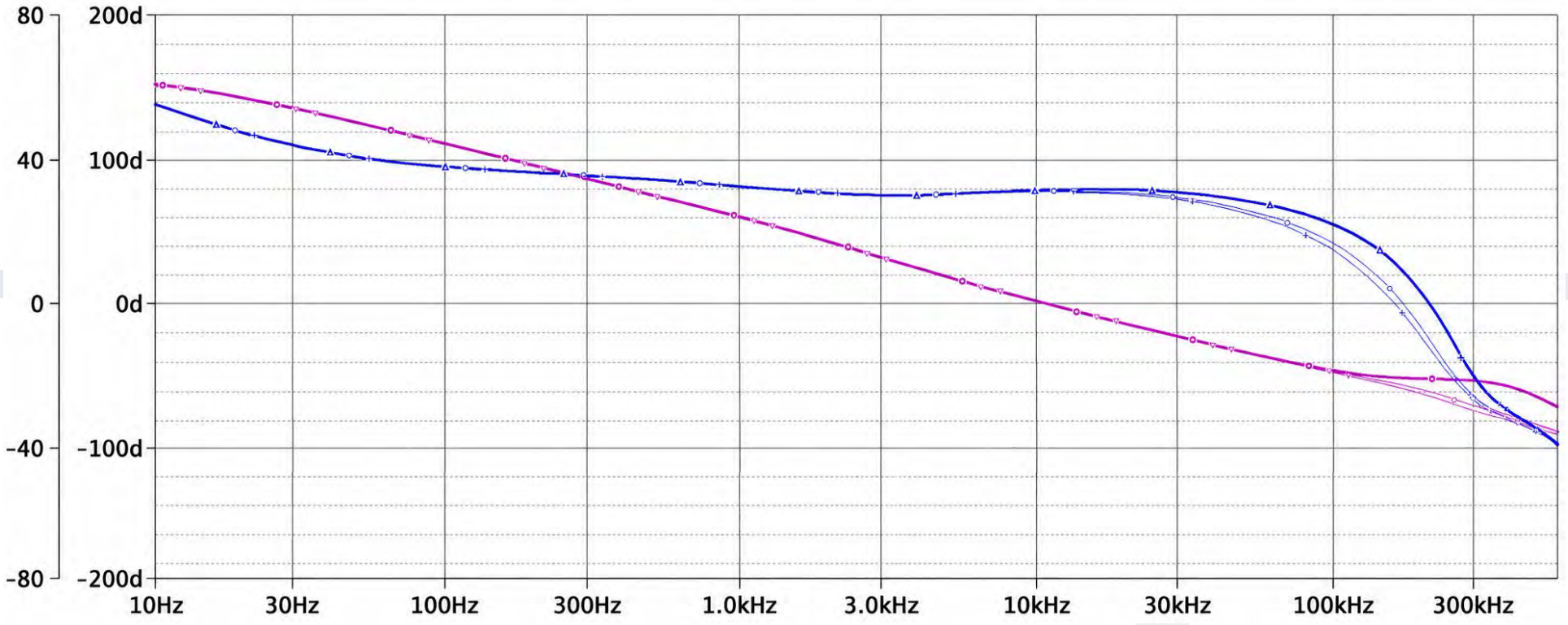
Implemented



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Current Mode Buck – Example 100W 12V to 3.3V Converter

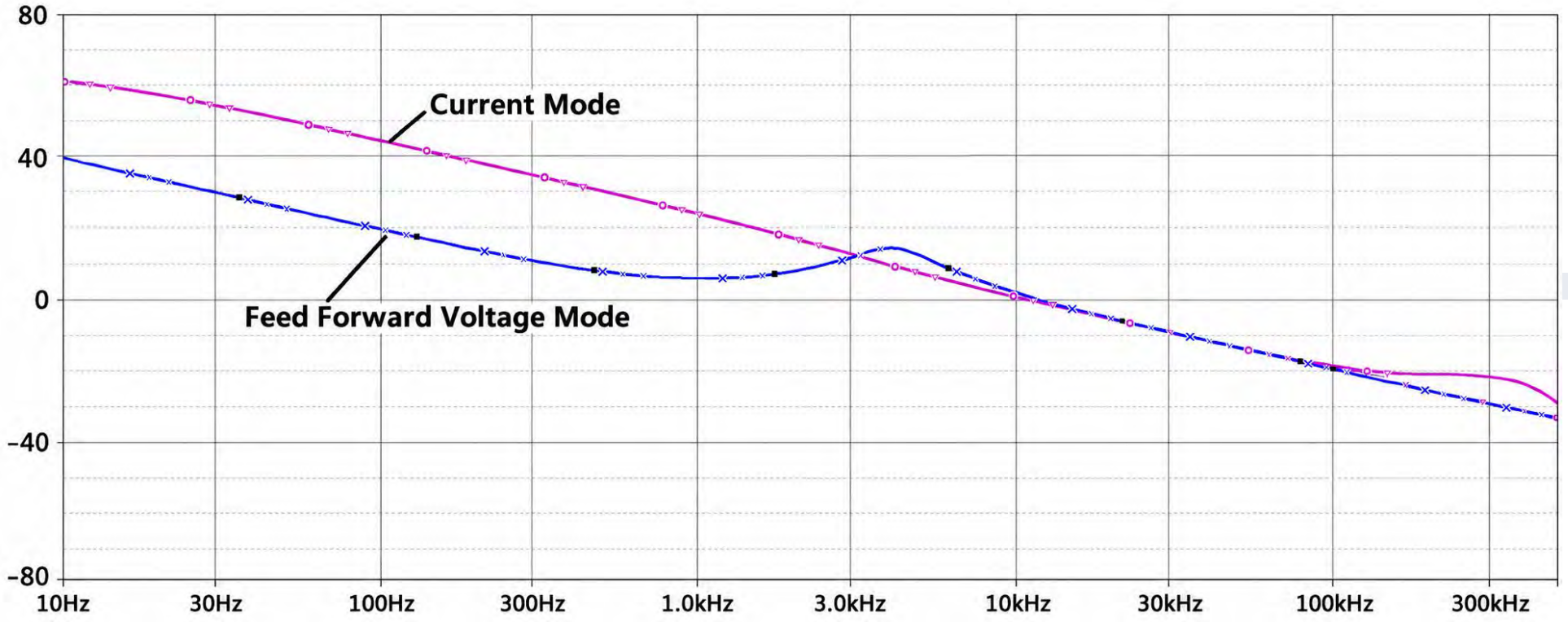
- Input voltage is swept from 6V to 16V.
- The gain does not vary with input voltage.



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Comparison – FF Voltage Mode vs. Current Mode– Example 100W 12V to 3.3V

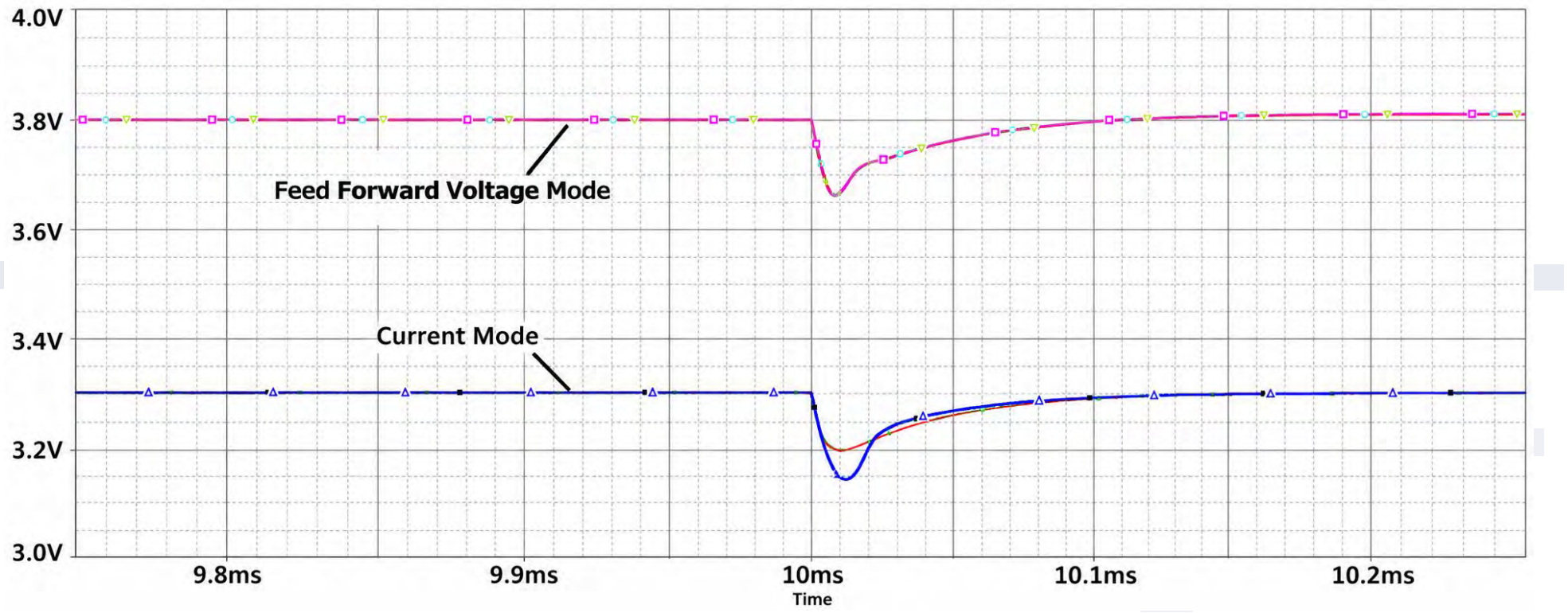
- Control Parameters set so that each crosses at 10 kHz
- Which will perform Better???



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Comparison – FF Voltage Mode vs. Current Mode– Example 100W 12V to 3.3V

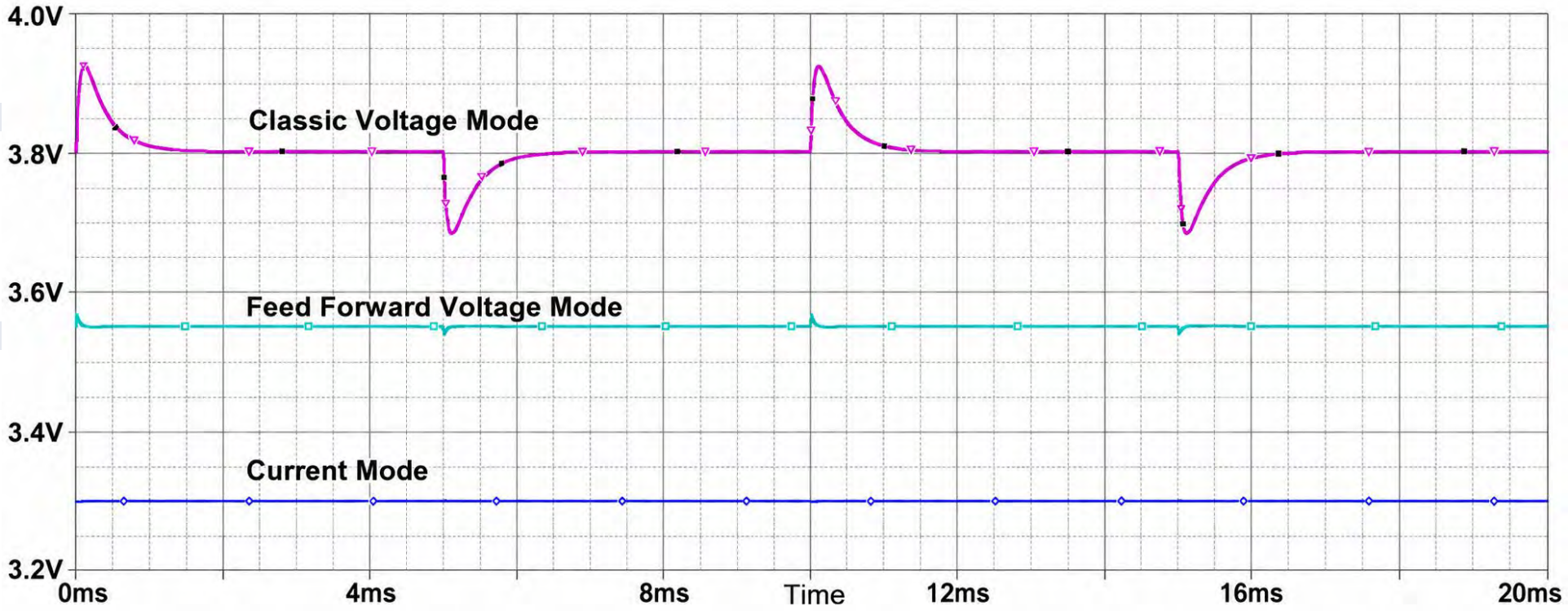
- Step – Load – About the same from ½ load to Full Load.
- Input voltage is swept from 6V to 16V.
- Feed Forward Voltage mode transient is more consistent.



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Comparison – FF Voltage Mode vs. Current Mode– Example 100W 12V to 3.3V

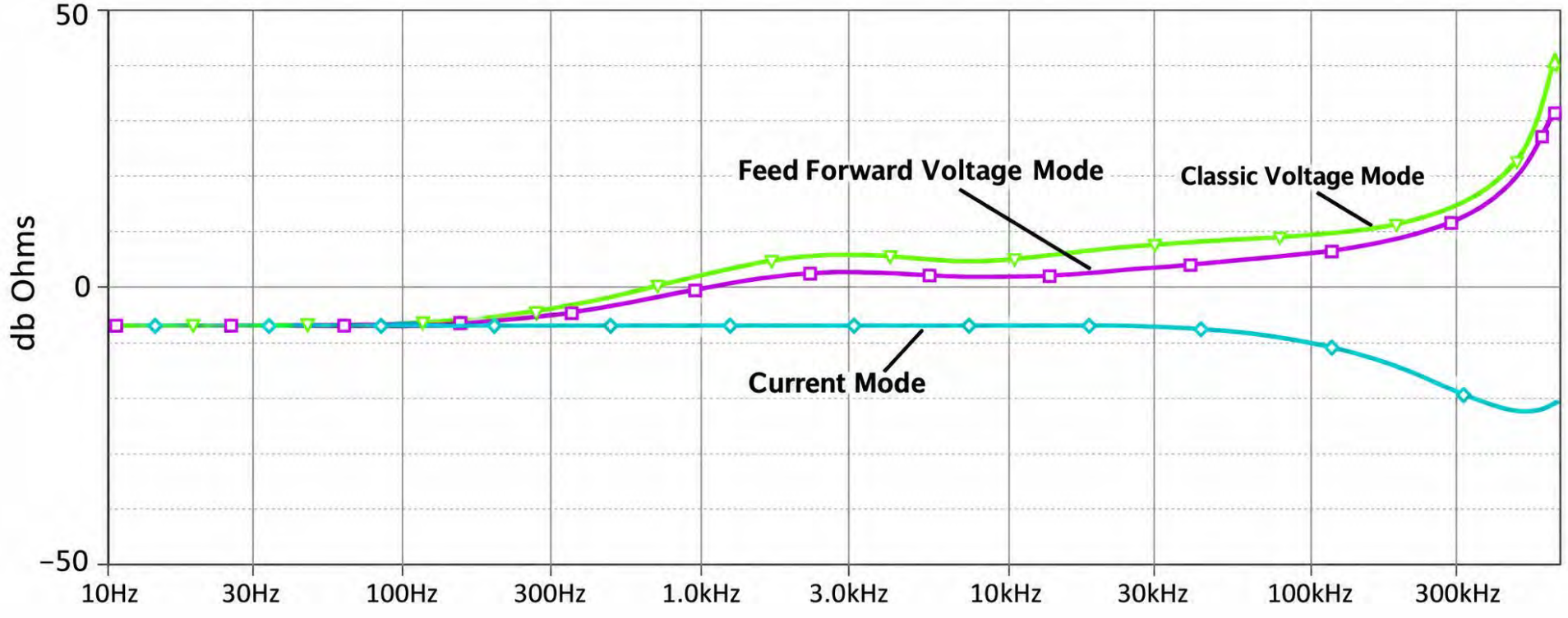
- Step – Input Voltage –Input voltage is Stepped from 12V to 16V.
- Feed Forward Voltage mode and Current mode provide dramatic improvement.



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Comparison – FF Voltage Mode vs. Current Mode– Example 100W 12V to 3.3V

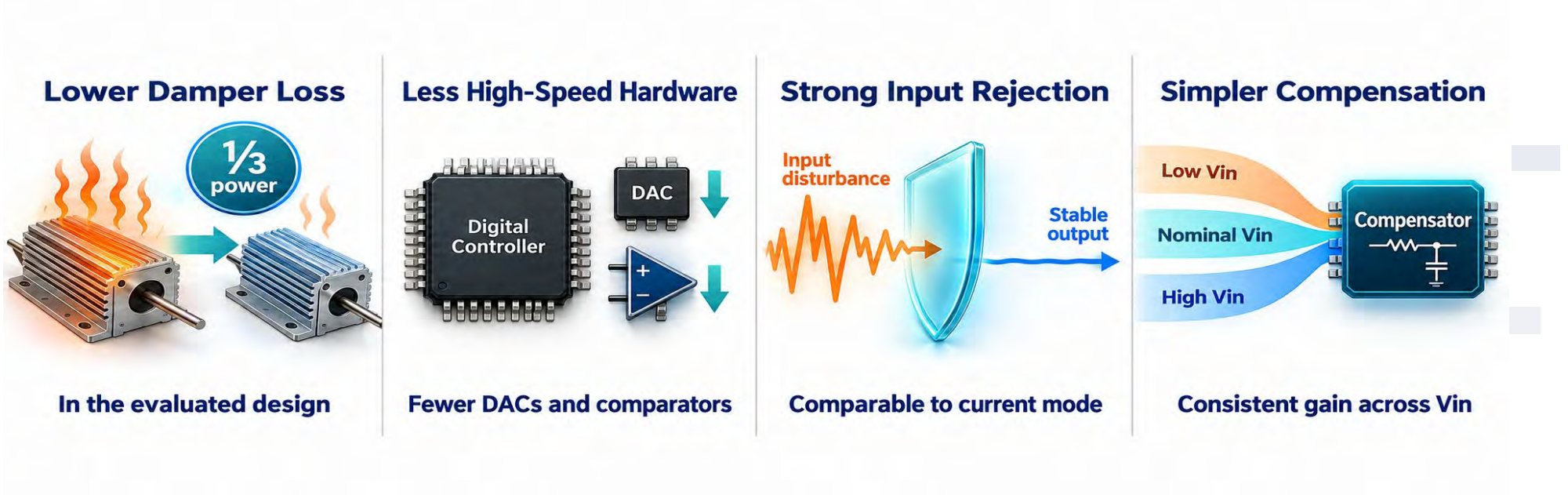
- Input impedance at 7V input.
- About a 10 db difference.
- The Feed Forward Voltage Mode saves 3x Size and Power in Input Filter Dampening Network.



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Comparison – FF Voltage Mode vs. Current Mode– Example 100W 12V to 3.3V

- What's the Pay off……..
  - Higher input impedance with voltage-mode control reduces damper dissipation by a factor of three in the evaluated design.
  - Digital voltage-mode control requires fewer high-speed DACs and comparators.
  - Voltage feedforward provides input-disturbance rejection comparable to current-mode control.
  - Feedforward simplifies compensation by making loop gain largely independent of input voltage.



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Feed Forward Voltage Mode Implementation

- Discrete Analog – High level of analysis and Verification.
- Analog ICs - Examples

Part	Release Date	Status
UCC28250	April 2010	ACTIVE
UCC28251	February 2013	ACTIVE
UCC35705	November 1999	ACTIVE

  - Disadvantage – Must analyze Lot to Lot and Temperature Variations
  - Limited Flexibility

- Digital Approach
  - Best Repeatability
  - Portable

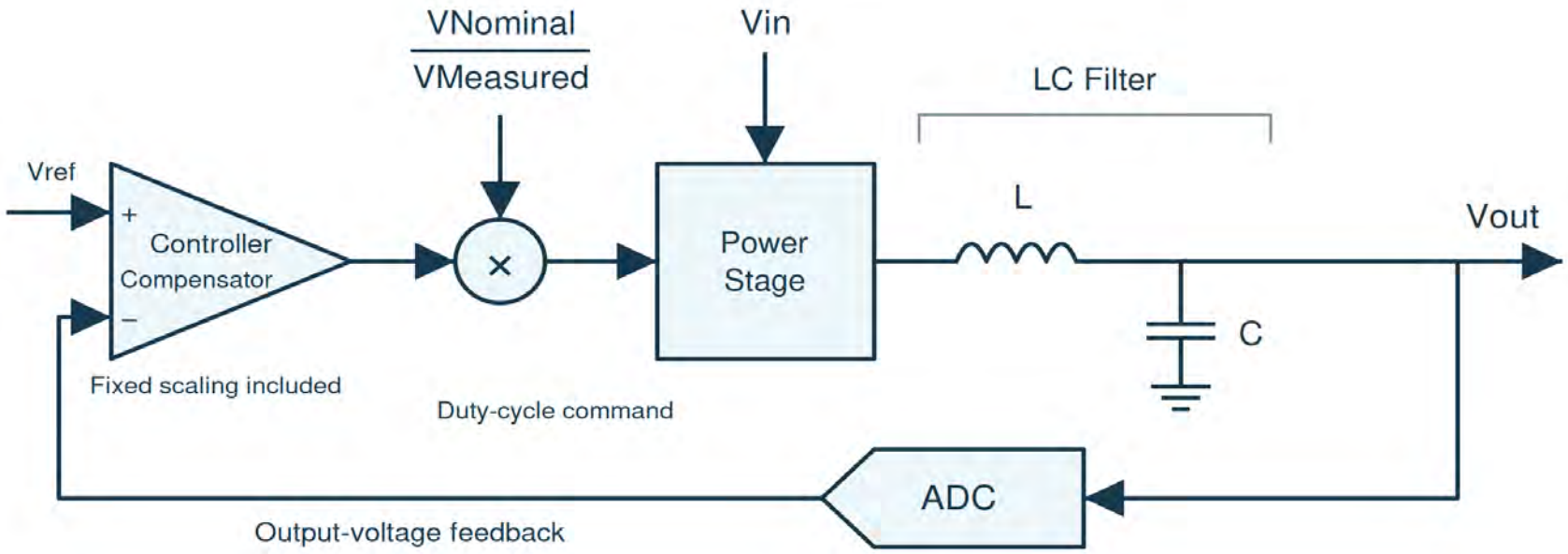


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Digital Implementation of Feed Forward Voltage Mode

- Conventional Voltage Mode: Multiply the compensator output by a fixed scaling factor to obtain the duty-cycle command.

- Feed Forward Voltage Mode: Apply an additional factor, $\frac{V_{Nominal}}{V_{Measured}}$, to adjust the duty-cycle command for changes in input voltage.



Digital Implementation of Feed Forward Voltage Mode

- For a microcontroller with DSP capability, we enter

$$G_n = (B_0 f_n + B_1 f_{n-1} + B_2 f_{n-2} + A_1 g_{n-1}) * \frac{V_{Nominal}}{V_{Measured}}$$

- If your micro has a built-in hardware math accelerator, the real-time division will add negligible processing time. Typically, 10-20 machine cycles. A typical overall math budget may be 300 machine cycles.

- Without the hardware accelerator, the live division might take hundreds of machine cycles.

- The Solution is Division by Recursive Multiplication.
  - (a special case of the Richardson iteration)

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Simple Single Pole Filter

It is Best to have a quick review of a basic construct
- the single pole low pass filter.

The LPF is represented in the z domain as follows...

$$H(z) := \frac{G(z)}{F(z)} \qquad H(z) := \frac{b_0}{1 - a_1 \cdot z^{-1}}$$

where... $a_1 := e^{-\alpha \cdot T_m}$ $\alpha := 2 \cdot \pi \cdot f_c$

$b_0 := 1 - e^{-\alpha \cdot T_m}$

Note that we want a leading 1 in the denominator. When we cross multiply and then transpose, we can get G(z) isolated on one side.

$$G(z) := b_0 \cdot F(z) + a_1 \cdot G(z) \cdot z^{-1}$$

$$g_n := b_0 \cdot f_n + a_1 \cdot g_{n-1}$$

This final form of the equation is something we can enter into our DSP code

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Convergence

$$g_n := b_0 \cdot f_n + a_1 \cdot g_{n-1}$$

For the equation above to provide stable results, $0 \le a_1 \le 1$

This is seen in how the equation responds to an impulse. After an impulse, g_n will take on a value. After the impulse, f_n will be 0.

If $a_1 := 0$, g_n will become 0 instantly.

If $a_1 := 1$, g_n will stay at g_{n-1} indefinitely.

If $0 < a_1 < 1$, g_n will decay exponentially towards 0.

If $1 < a_1$, g_n will increase indefinitely.

If $-1 < a_1 < 0$, g_n will decay, but oscillate between positive and negative values.

If $a_1 := -1$, g_n will oscillate between $-g_{n-1}$ and g_{n-1} .

If $a_1 < -1$, $|g_n|$ will increase indefinitely.

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Division by Recursive Multiplication

We wish to get a result …

$$G(z) := \frac{F_{nom}}{F(z)}$$

To get the leading 1, add $1 - z^{-1}$ to the denominator.
Note that z is a phasor whose value is $e^{lj \cdot 2 \cdot \pi \cdot f \cdot Hz \cdot T_m}$.
At zero frequency, z equals 1. Therefore, the steady state value is unaffected by adding this to the denominator.

$$G(z) := \frac{F_{nom}}{1 - z^{-1} + F(z)}$$

Now multiply $F(z)$ by z^{-1}. Again, this will not effect the steady state value.

$$G(z) := \frac{F_{nom}}{1 - (1 - F(z)) \cdot z^{-1}}$$

As was the case with the LPF, to achieve stability, we must bound $1 - F(z)$ between 0 and 1.
This is equivalent to bounding $F(z)$ between 0 and 1.
Modify the equation slightly, which again, will not effect the steady state value.

$$G(z) := \frac{\frac{F_{nom}}{F_{max}}}{1 - \left(1 - \frac{F(z)}{F_{max}}\right) \cdot z^{-1}}$$

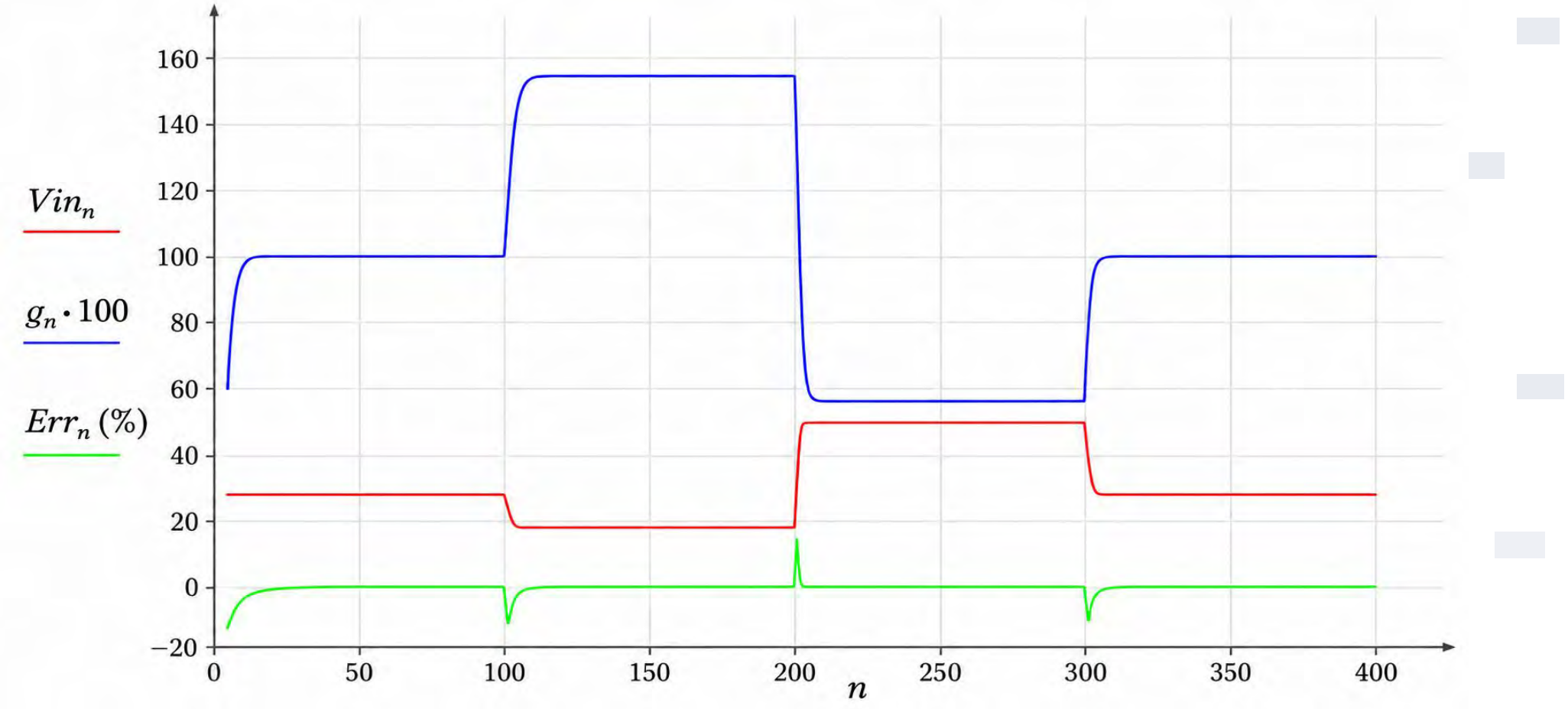
Cross-multiplying, transposing and a simple transform yields the final form that can be entered into DSP code.

$$g_n := \frac{F_{nom}}{F_{max}} + g_{n-1} - \frac{g_{n-1} \cdot f_n}{F_{max}}$$

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Division by Recursive Multiplication

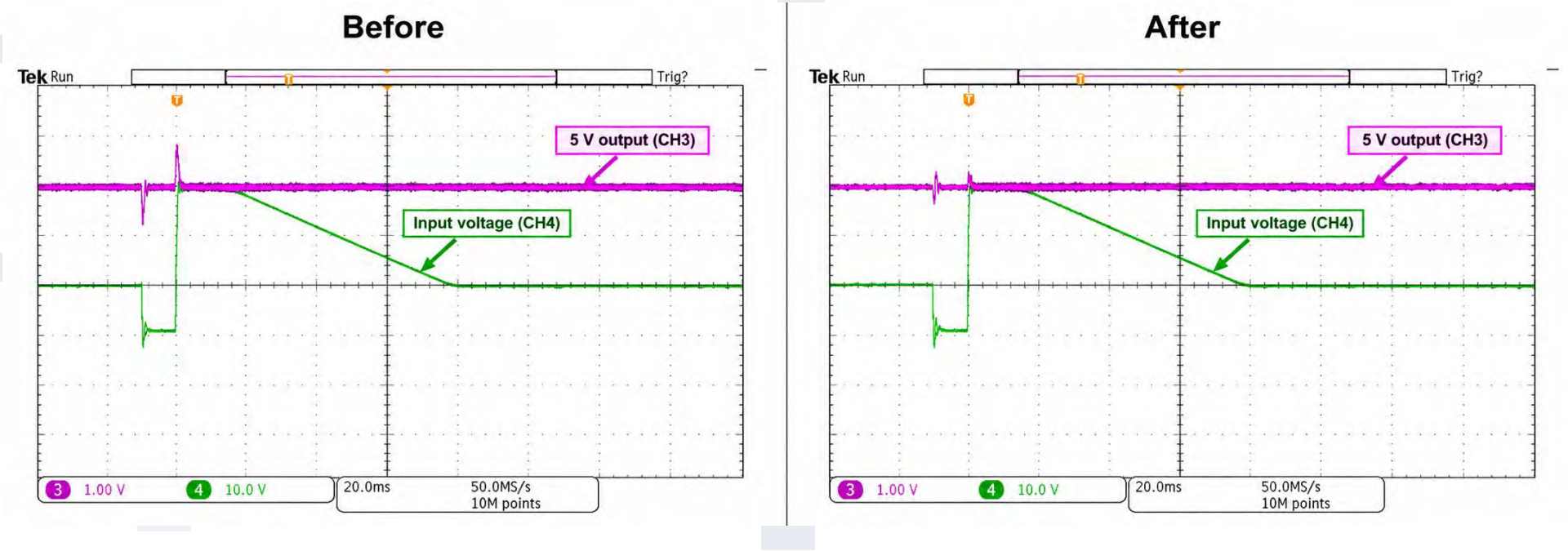
- The process working against a popular 18 to 50V Transient
- Less than 20% error on the first iteration



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Division by Recursive Multiplication – Live Implementation

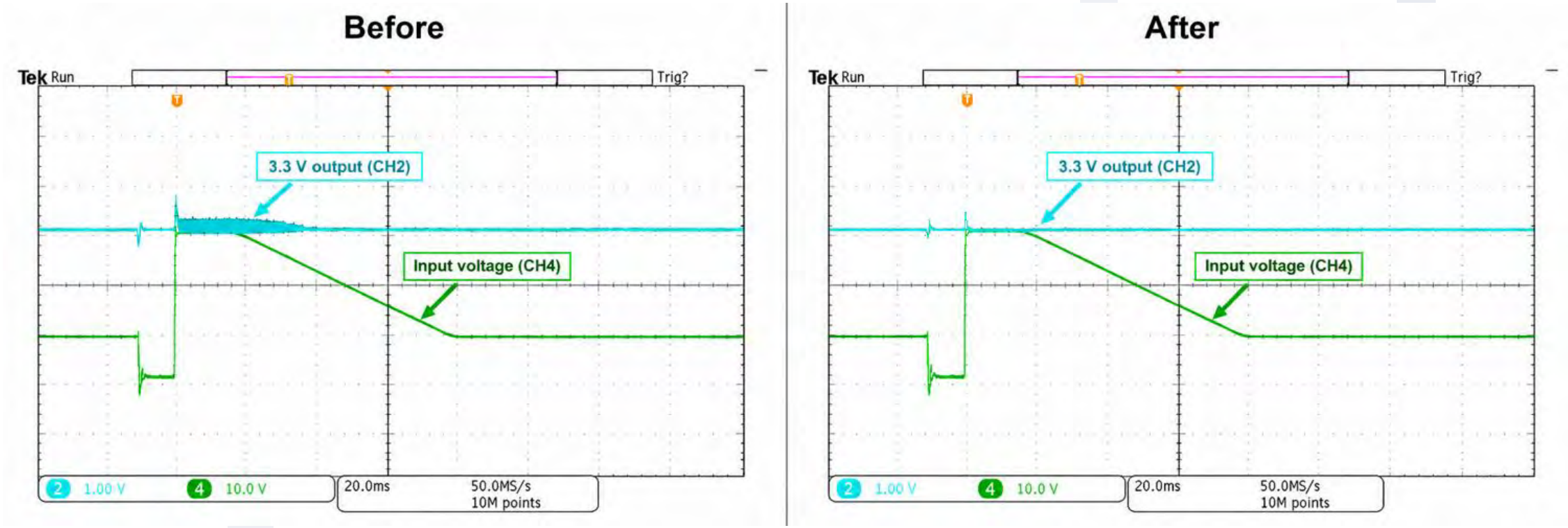
- Here the routine is working on a live lab unit – 28V Nominal to 5V isolated Converter.
- Transients reduced from 0.85V to 0.35V



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Division by Recursive Multiplication – Live Implementation

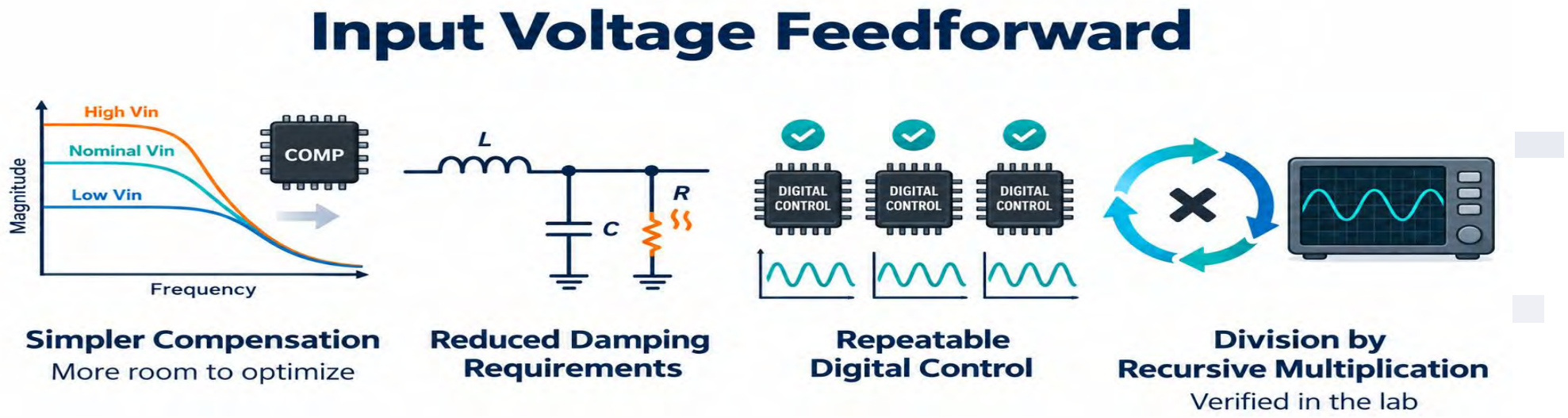
- Live lab unit – 28V Nominal to 3.3V isolated Converter.
- Not only improved transients, but instability at high voltage is gone.



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Conclusion

- Input Voltage Feed Forward…
  - Simplifies and allows optimization of compensation Loops.
  - Substantial reduction in dampening requirements.
- The Digital solution improves repeatability.
- Division by Recursive Multiplication was introduced and verified by lab results.



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