

Practical System Modelling using Bench Measurements of Plant Transfer Functions



A Leading Provider of Smart, Connected and Secure Embedded Control Solutions



Presented by **Andreas Reiter**
March 9th 2022

Agenda

- **System Modelling Challenges**
- **Frequency Domain Design: The Basics**
- **Plant Frequency Response Measurements**
 - Constant Gain Feedback Loop
 - Digitally Decoupled Injection (non-invasive)
- **Summary**

- **Appendix:**
 - In-Chip Measurement

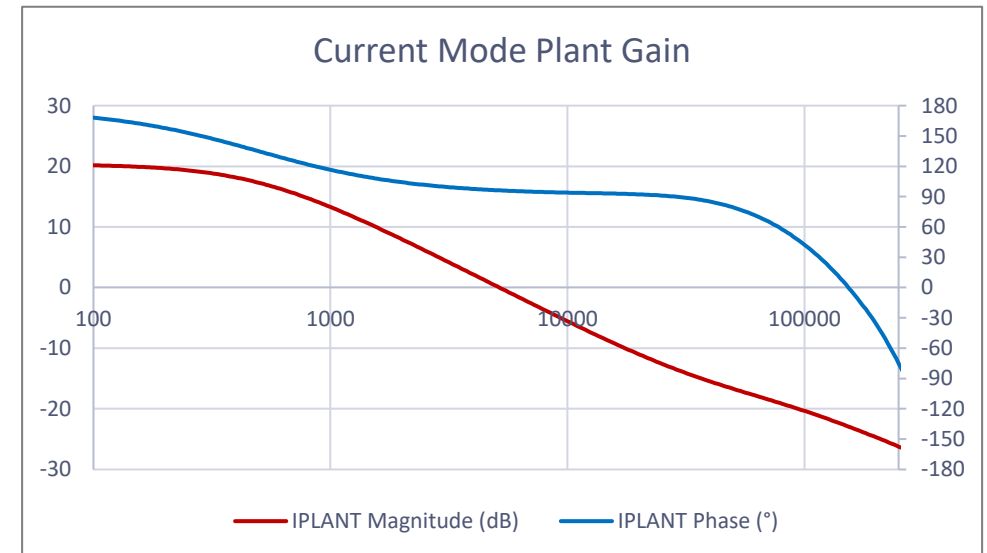
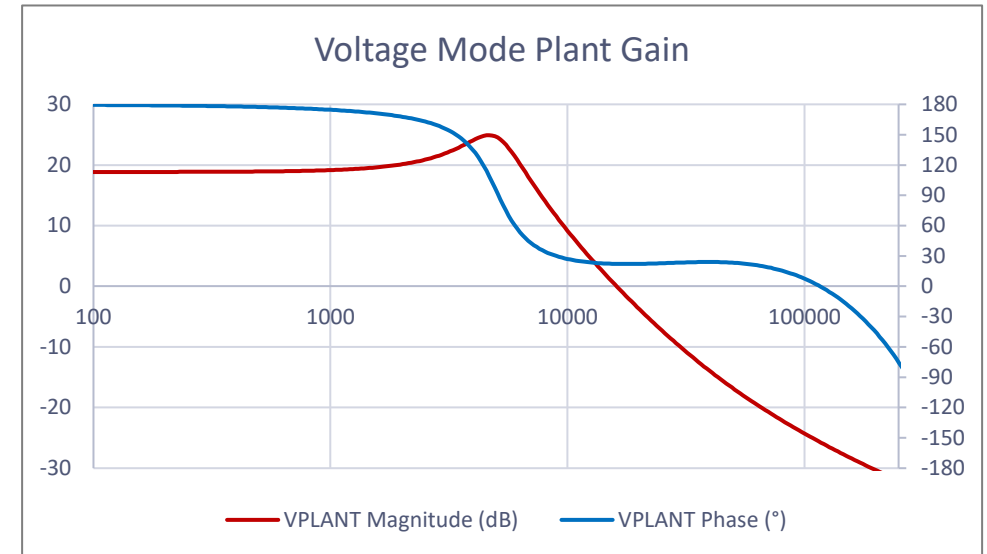
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Why Measuring the Plant Gain Matters

- The plant transfer function is the essential system component of every power supply design
- The plant frequency response is influenced by the following factors:
 - Passive-reactive power filter circuit
 - Excitation method (commutation and control mode)
 - Outer operating conditions (voltage levels)
 - Load condition (DCM, CRM, CCM)
- Hence, plant transfer functions are fundamentally different, even if the power supply topology itself remains unchanged
- Switch-mode power supplies are not continuous time domain filters!

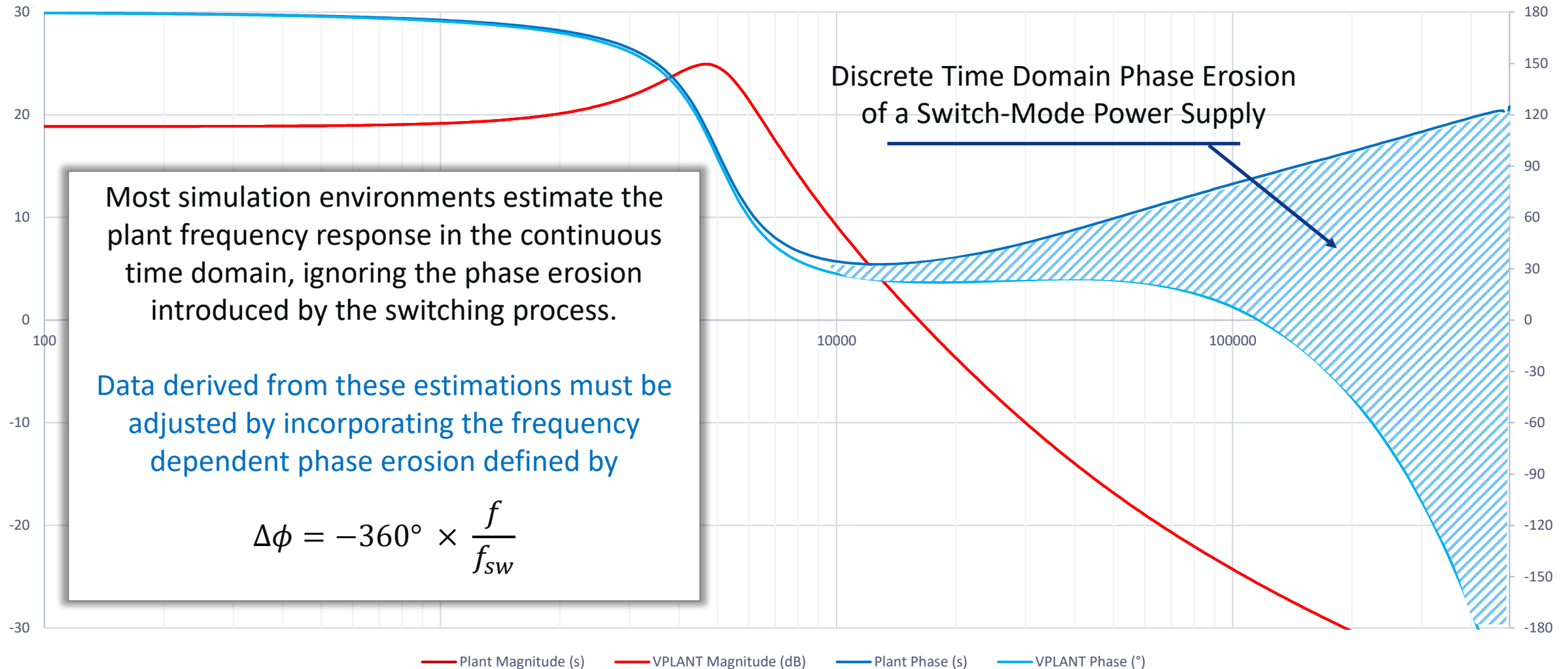


Common Design Steps

- **Circuit Design & Layout** *including Simulation*
- **Prototype / Hardware Validation**
 - Adjusting circuit components
 - Fixing hardware issues
 - *Validation of simulation results*
 - *Safely closing the loop*
- **Feature Development**
 - Performance Test and Optimization
- **Design Validation Test & Documentation**
 - Functional Tests
 - EMI, Safety & Robustness

System Modeling Challenges

Continuous vs. Discontinuous Time Domain Plant Gain



System Modeling Challenges

- Many common design guidelines don't hold up in modern designs

- **Examples:**

- H. Dean Venable's k-factor modulation indirectly accommodates for the switching process phase erosion by adding phase boost to an analog compensation filter

- Assumptions:

- Feedback loop is continuous time domain only
- Q-factor of power filter is ~ 0.5 (ideally damped)



- *Not applicable in digital designs*
- *Not feasible for power supplies with efficiencies > 92% !*

- Voltage Mode Controlled Power Supplies are always stable

- Assumption:

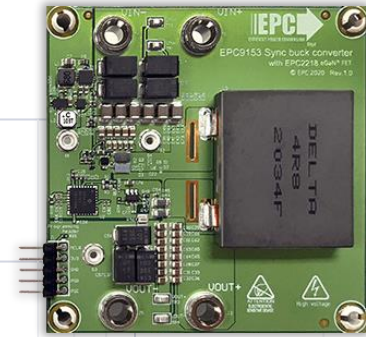
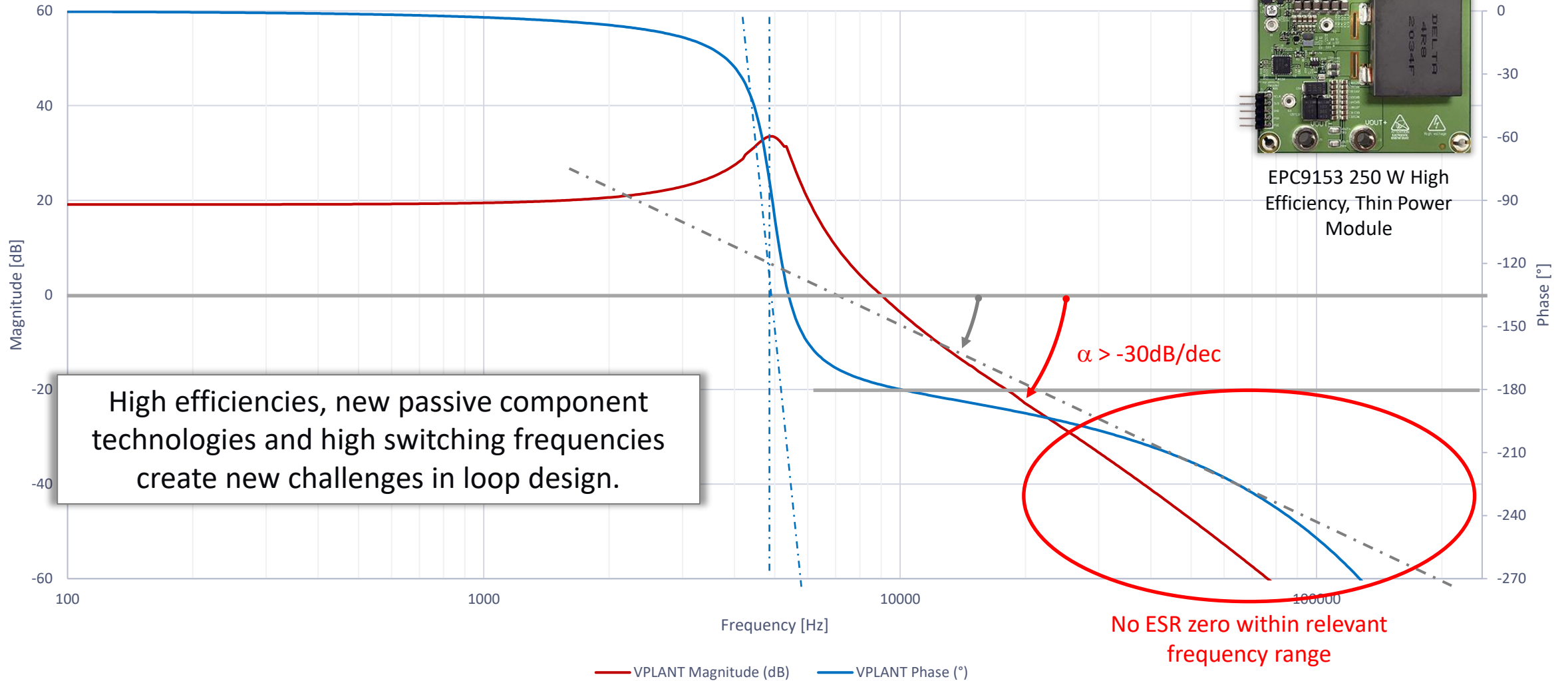
- Dominant ESR zero lies within switching frequency range
- Phase remains $> -180^\circ$
(Does not consider switching process phase erosion)



- *Not true for most of today's designs*
- *Outright wrong:
Over-simplified system model*

Plant Transfer Function of 98% Efficient Buck Converter

EPC9153 Plant Gain

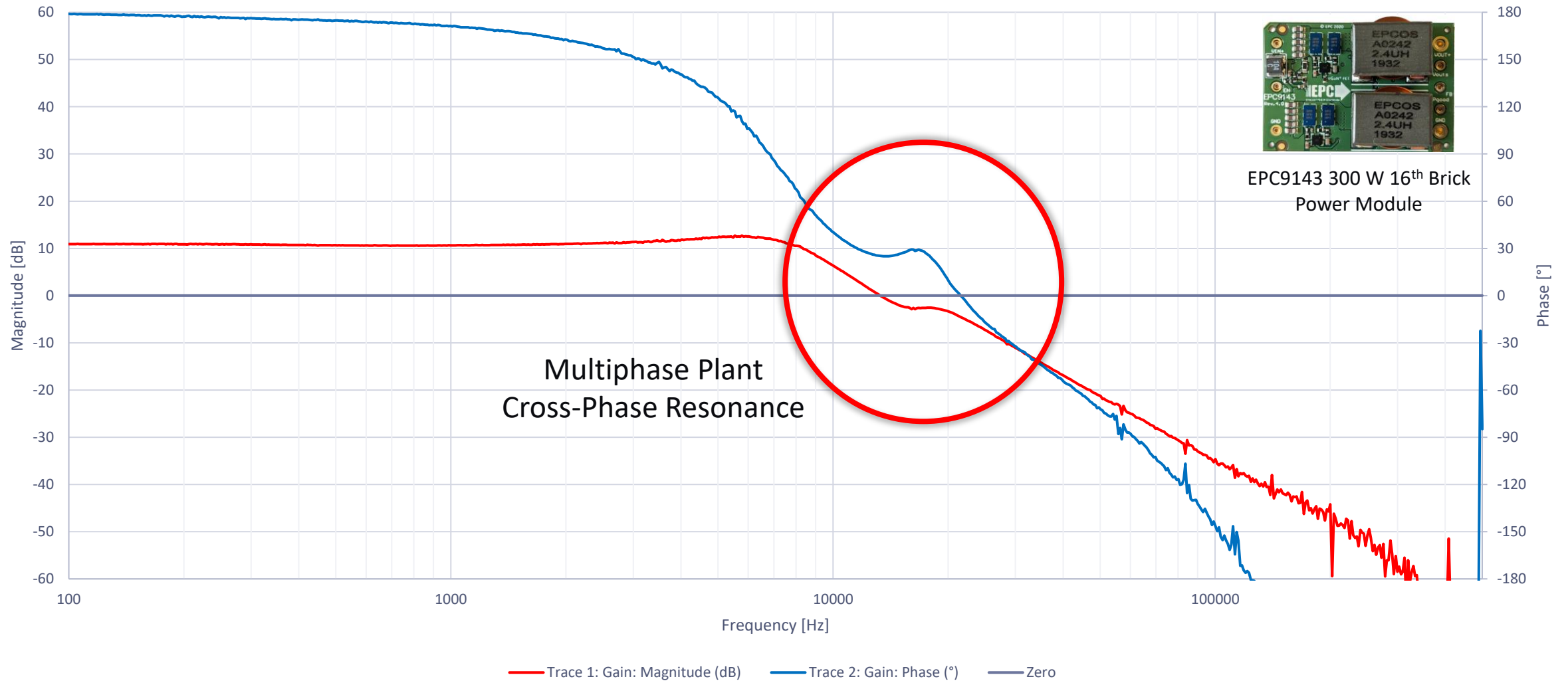


EPC9153 250 W High Efficiency, Thin Power Module

High efficiencies, new passive component technologies and high switching frequencies create new challenges in loop design.

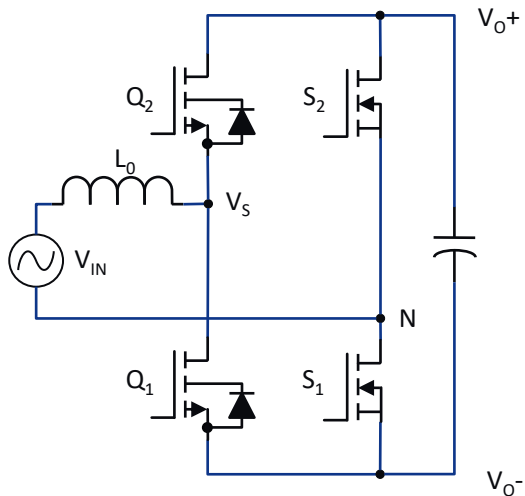
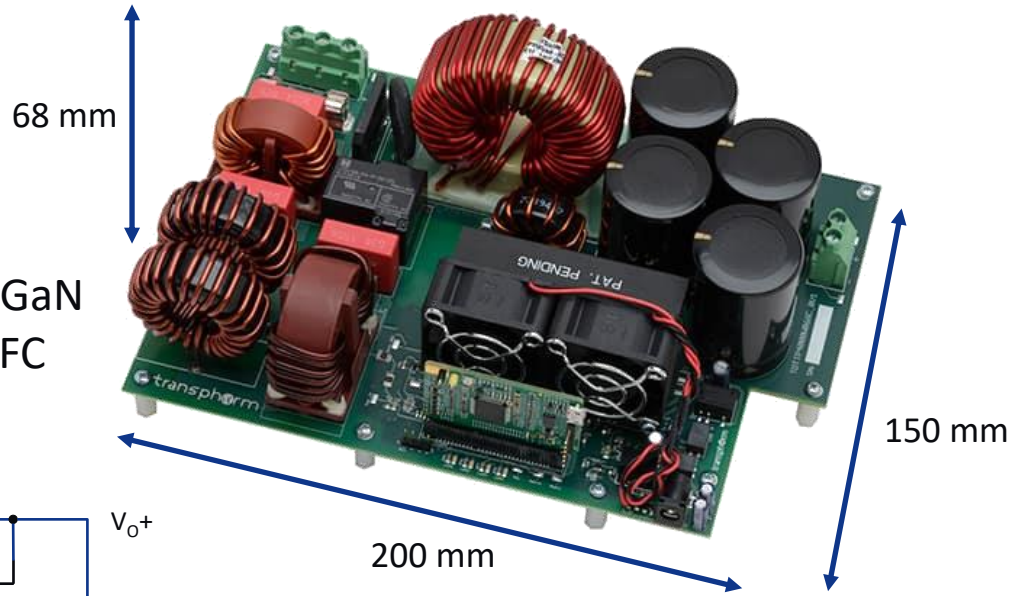
Capturing Circuit Artefacts

EPC9143 Plant Transfer Function



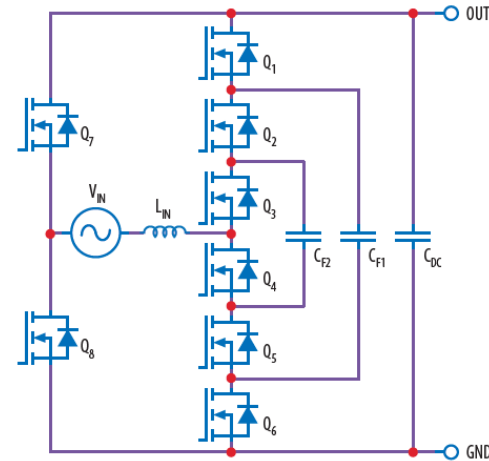
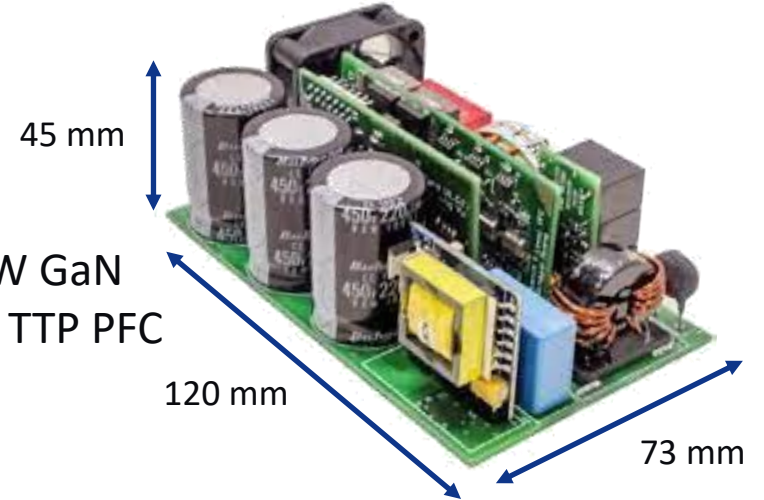
Continuous Topology Evolution

2.5 kW GaN
TTP PFC



Conventional Totem-Pole Bridgeless PFC
99% Efficiency @ 160 kHz Switching Frequency

3 kW GaN
FCML TTP PFC



4-Level FCML Totem-Pole Bridgeless PFC
99% Efficiency @ 150 kHz Switching Frequency*

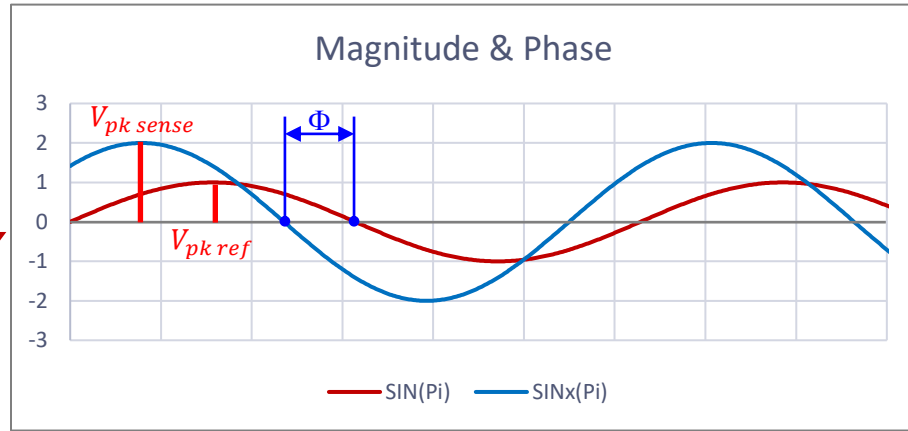
*: $f_L = f_{Q(1-6)} \times 3$ results in 72% reduction in V-s

Agenda

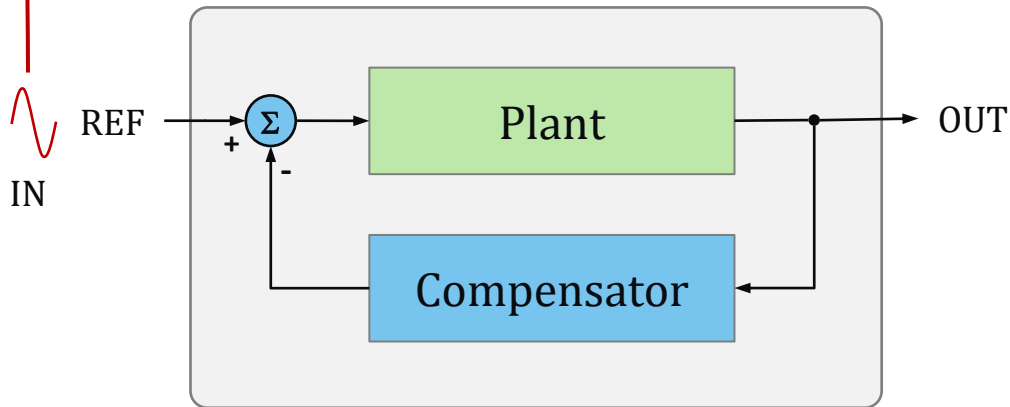
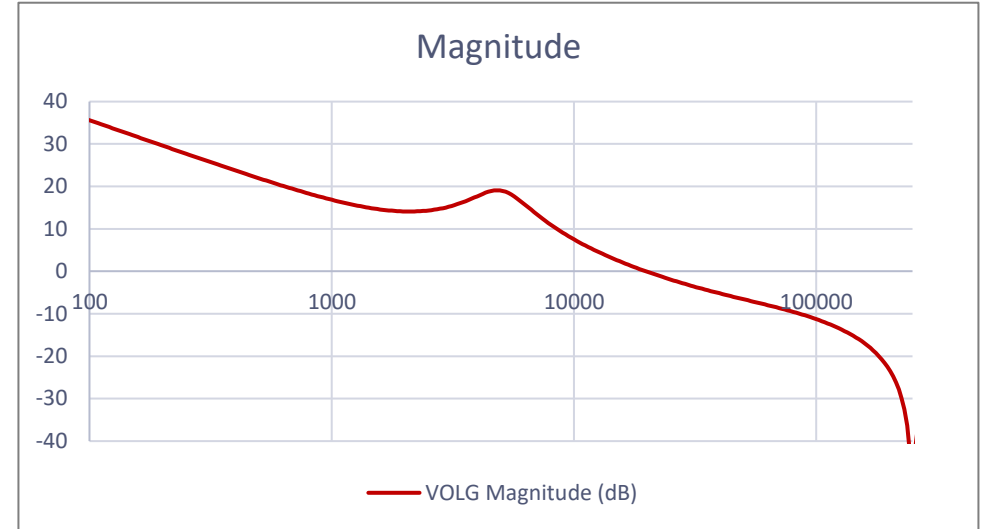
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The Basics



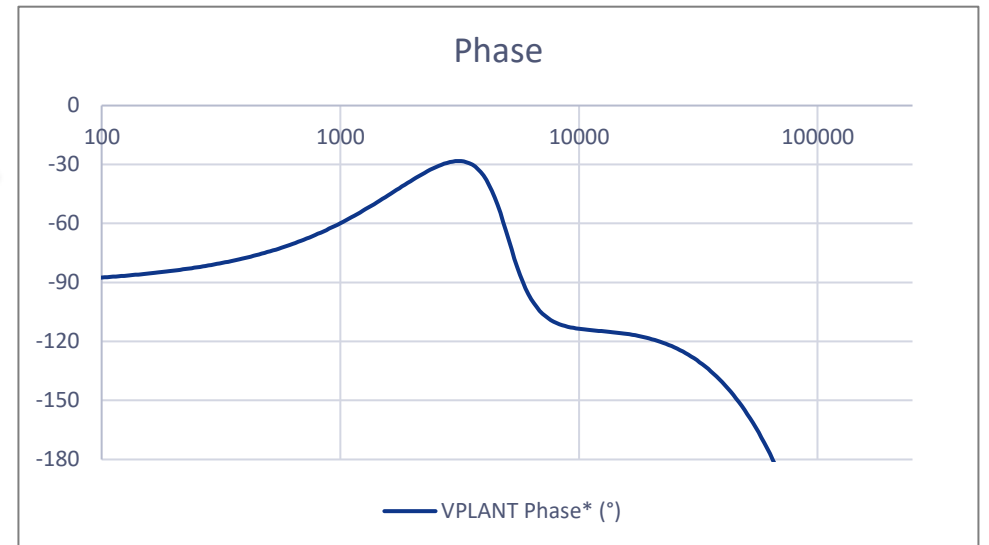
$$Mag = \frac{V_{pk\ sense}}{V_{pk\ ref}}$$



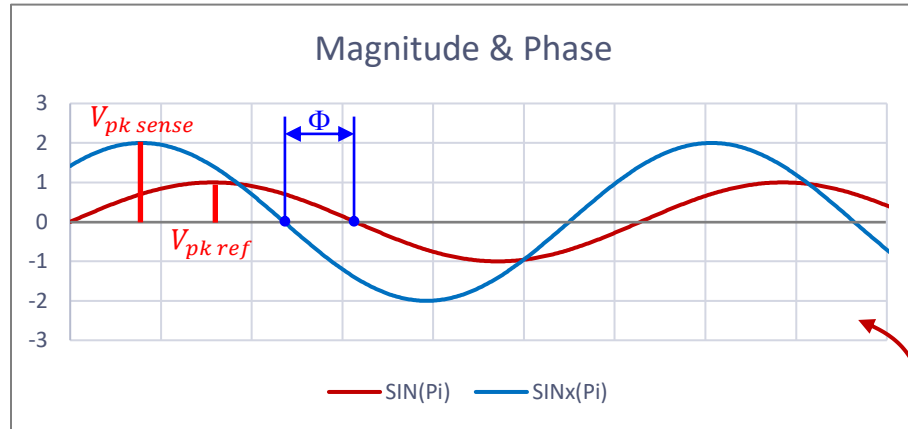
$$\Phi_{sense} - \Phi_{ref}$$

$$G_{CL}(s) = \frac{G(s)}{1 - G(s)H(s)}$$

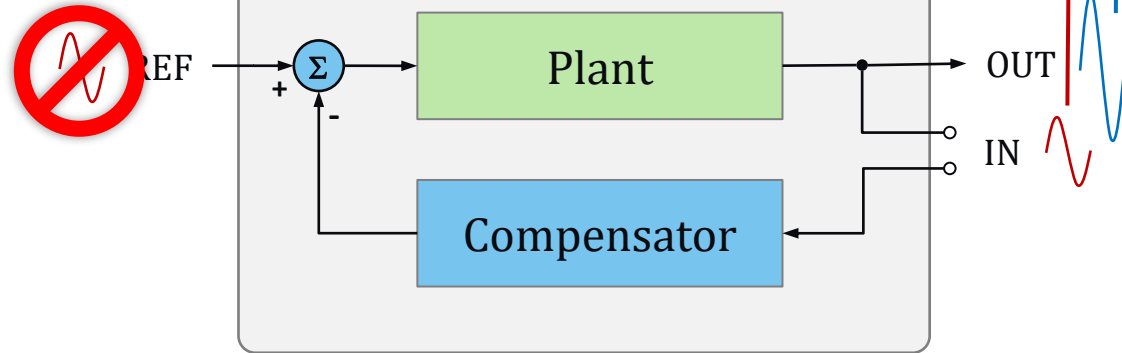
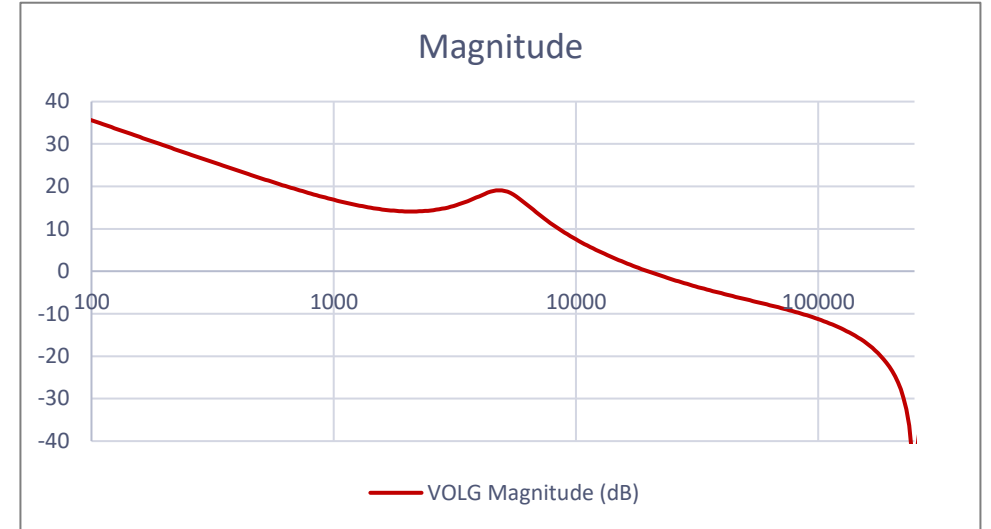
Aspect of Analysis
Open Loop Gain in
the Closed Loop
System



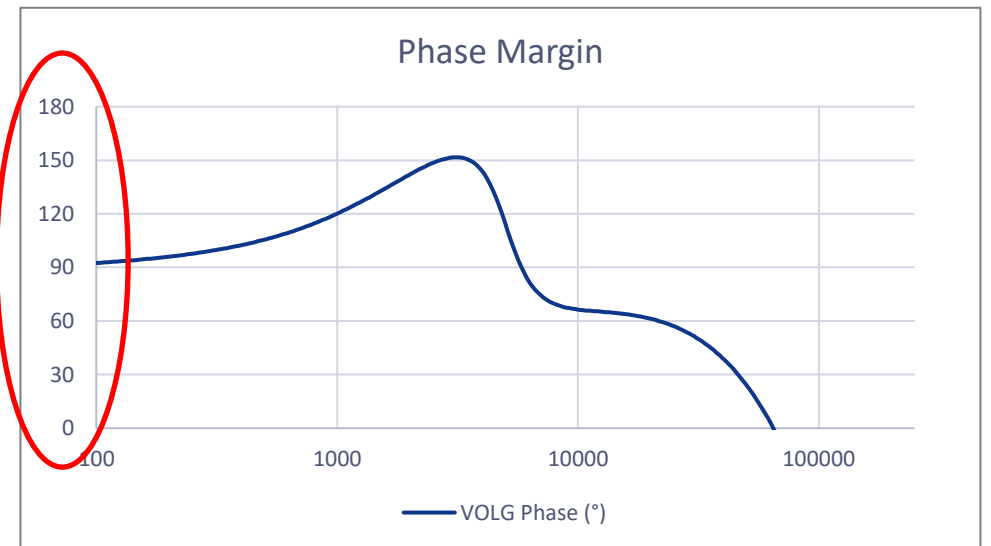
The Basics



$$Mag = \frac{V_{pk\ sense}}{V_{pk\ ref}}$$

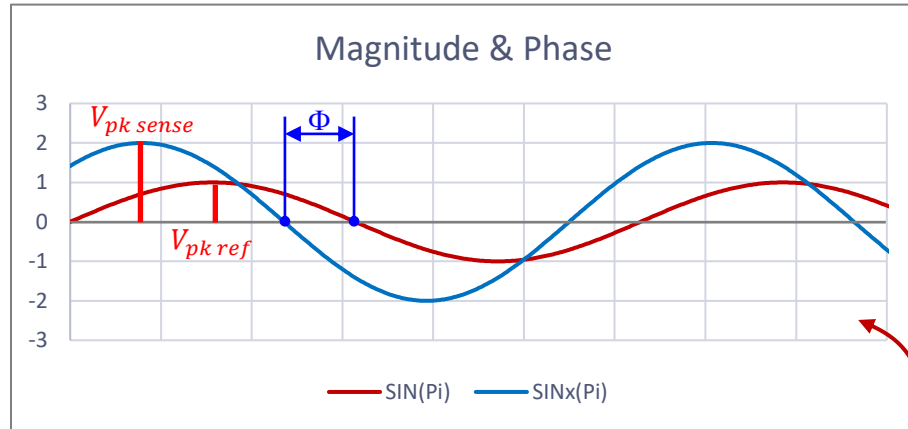


$$\Phi_{sense} - \Phi_{ref}$$

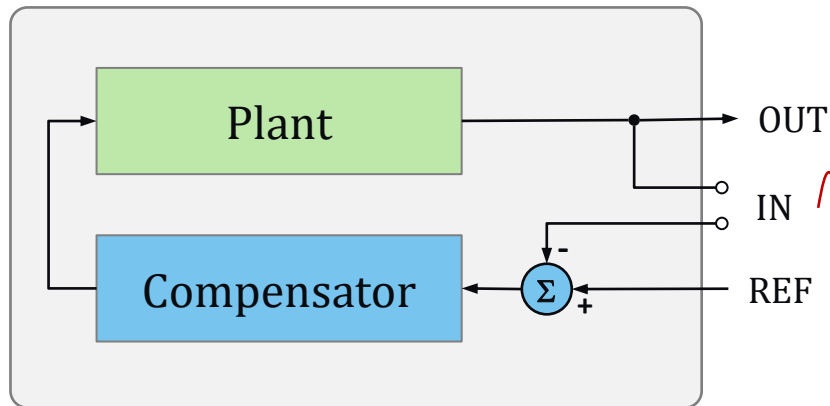
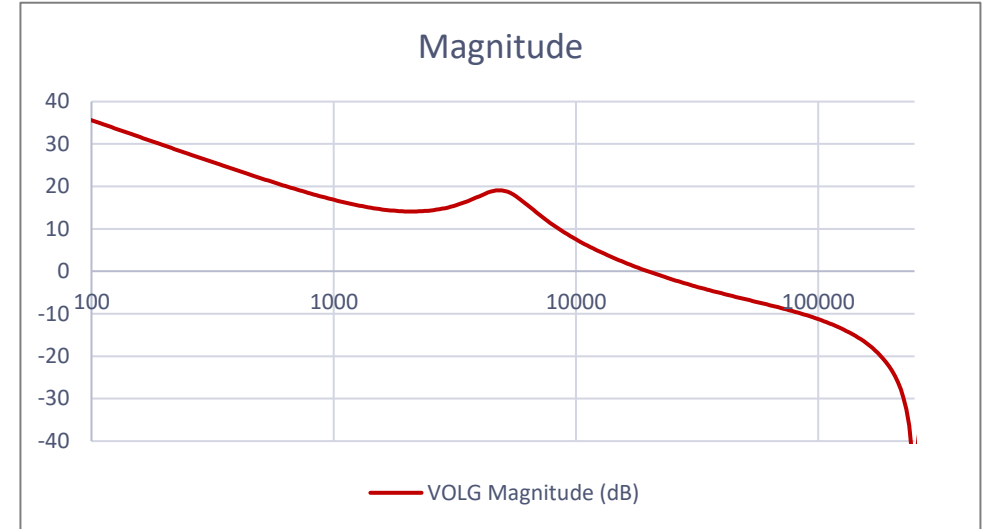


$$G_{CL}(s) = \frac{G(s)}{1 + G(s)H(s)}$$

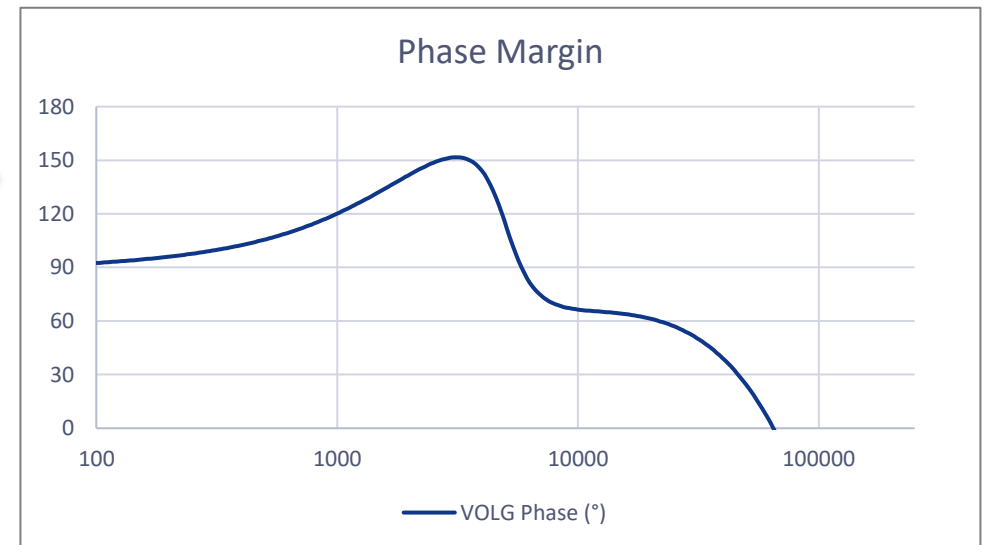
The Basics



$$Mag = \frac{V_{pk\ sense}}{V_{pk\ ref}}$$



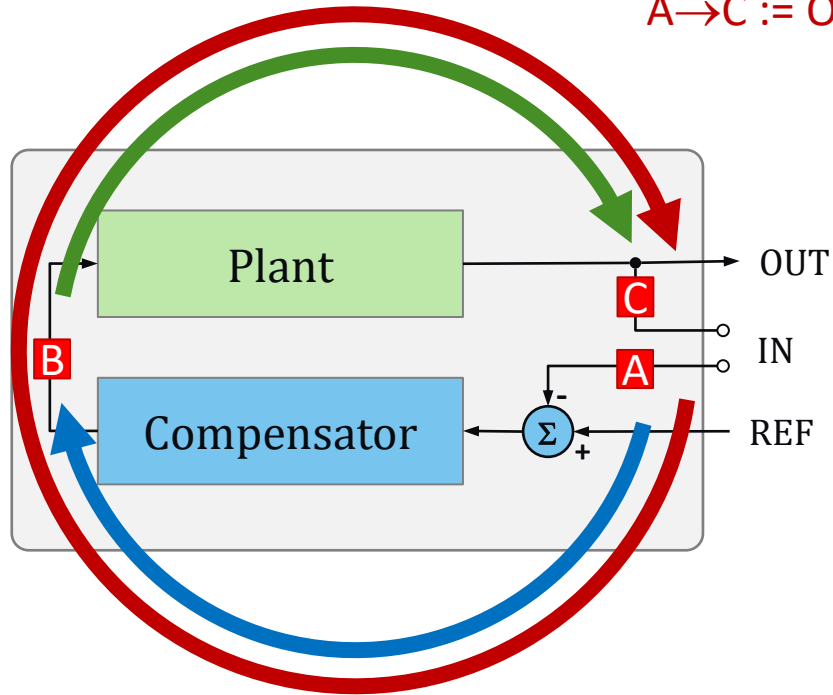
$$\Phi_{sense} - \Phi_{ref}$$



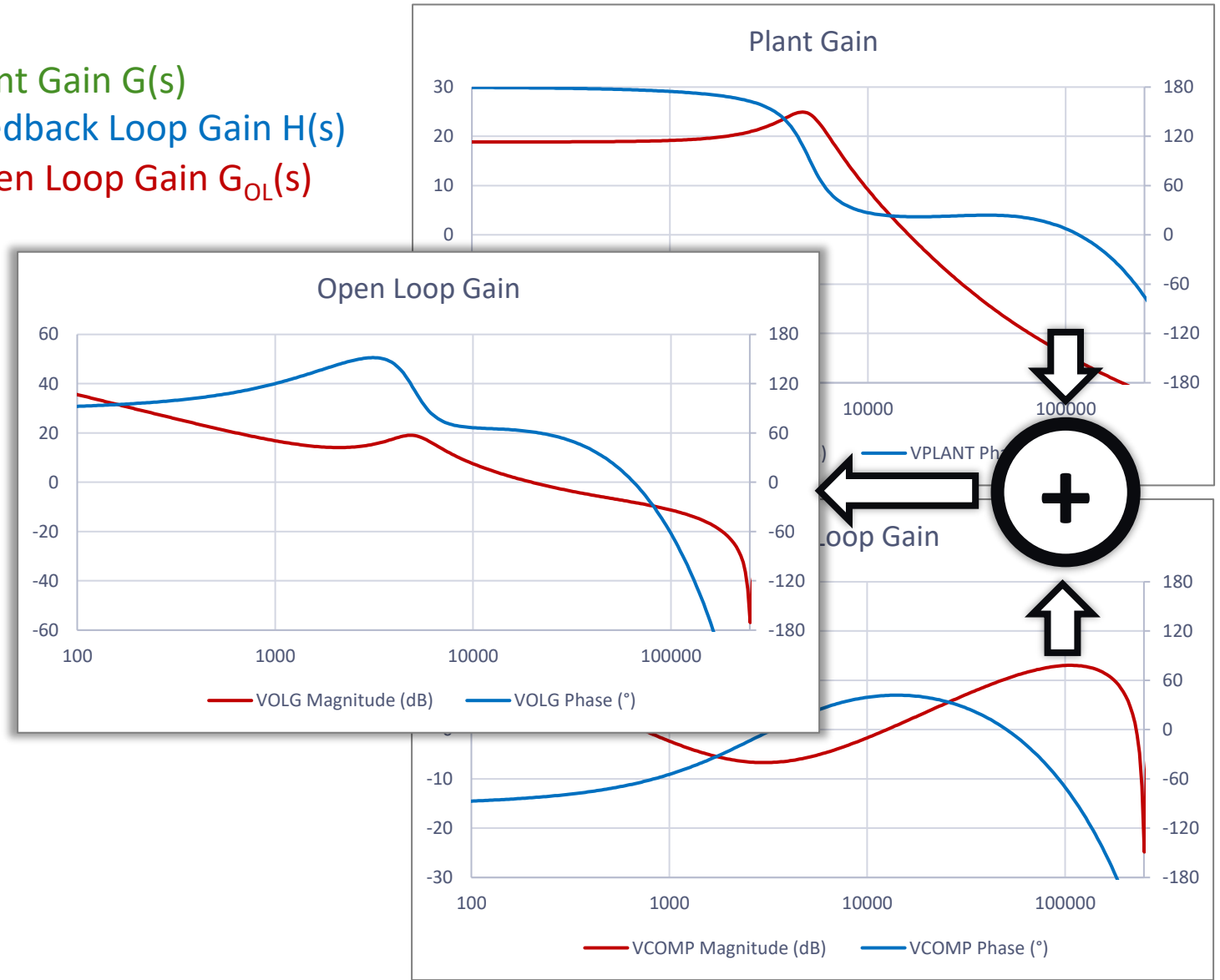
$$G_{CL}(s) = \frac{G(s)}{1 + G(s)H(s)}$$

The Basics

$B \rightarrow C := \text{Plant Gain } G(s)$
 $A \rightarrow B := \text{Feedback Loop Gain } H(s)$
 $A \rightarrow C := \text{Open Loop Gain } G_{OL}(s)$

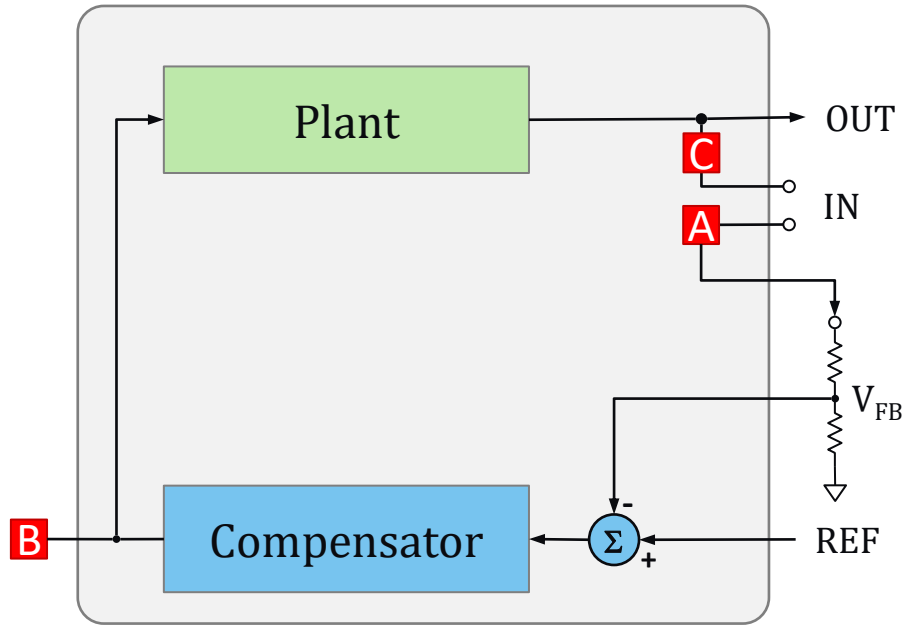


$$G_{OL}(s) = G(s) \times H(s)$$

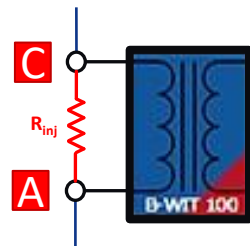
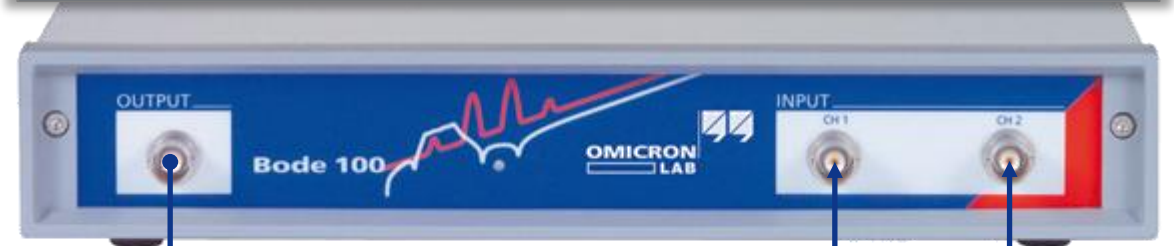
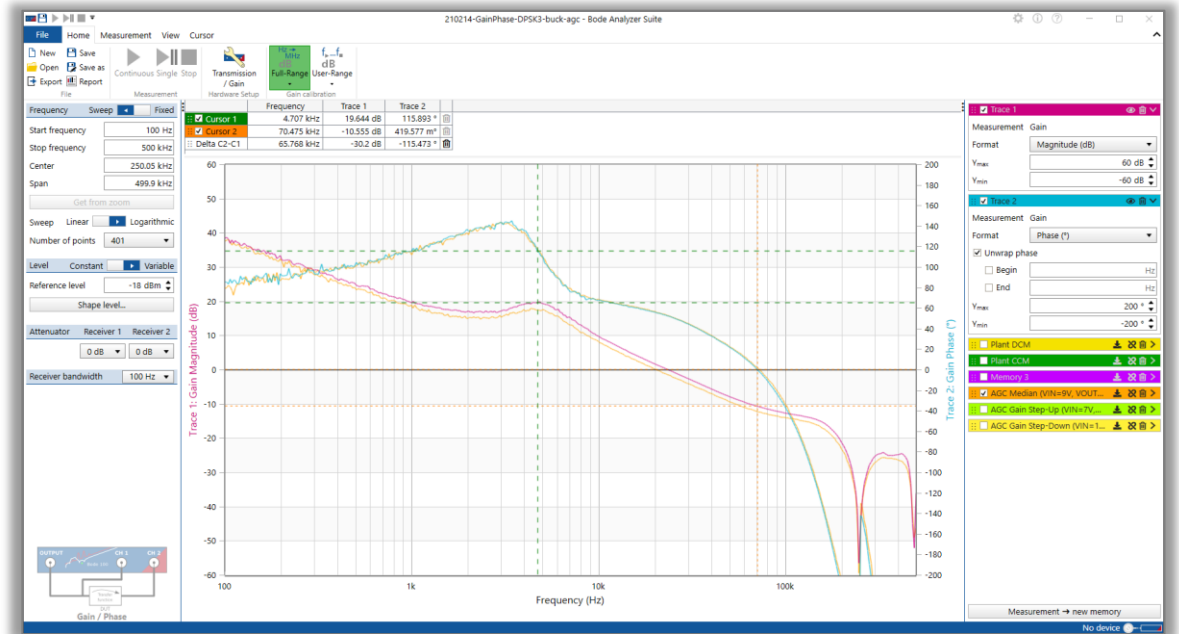


Warning!

Signal



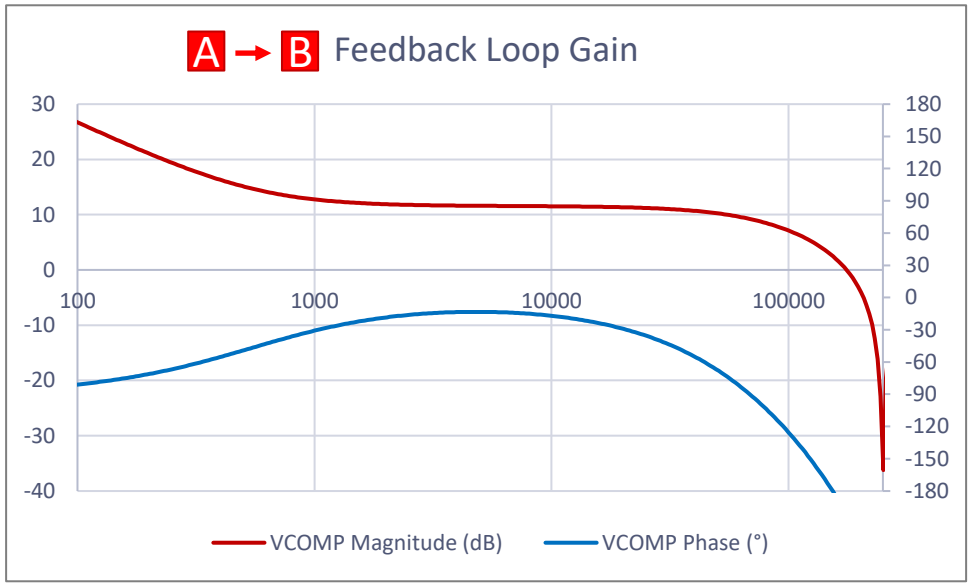
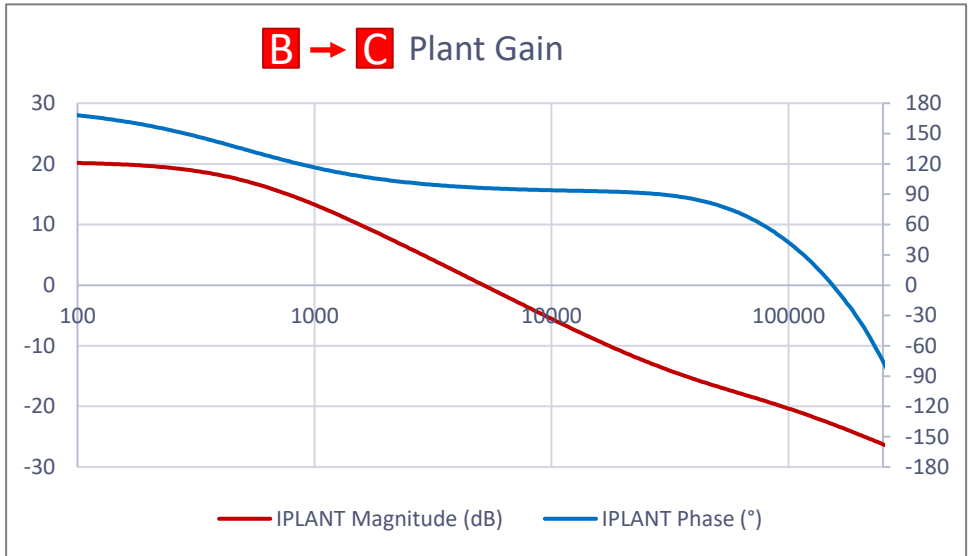
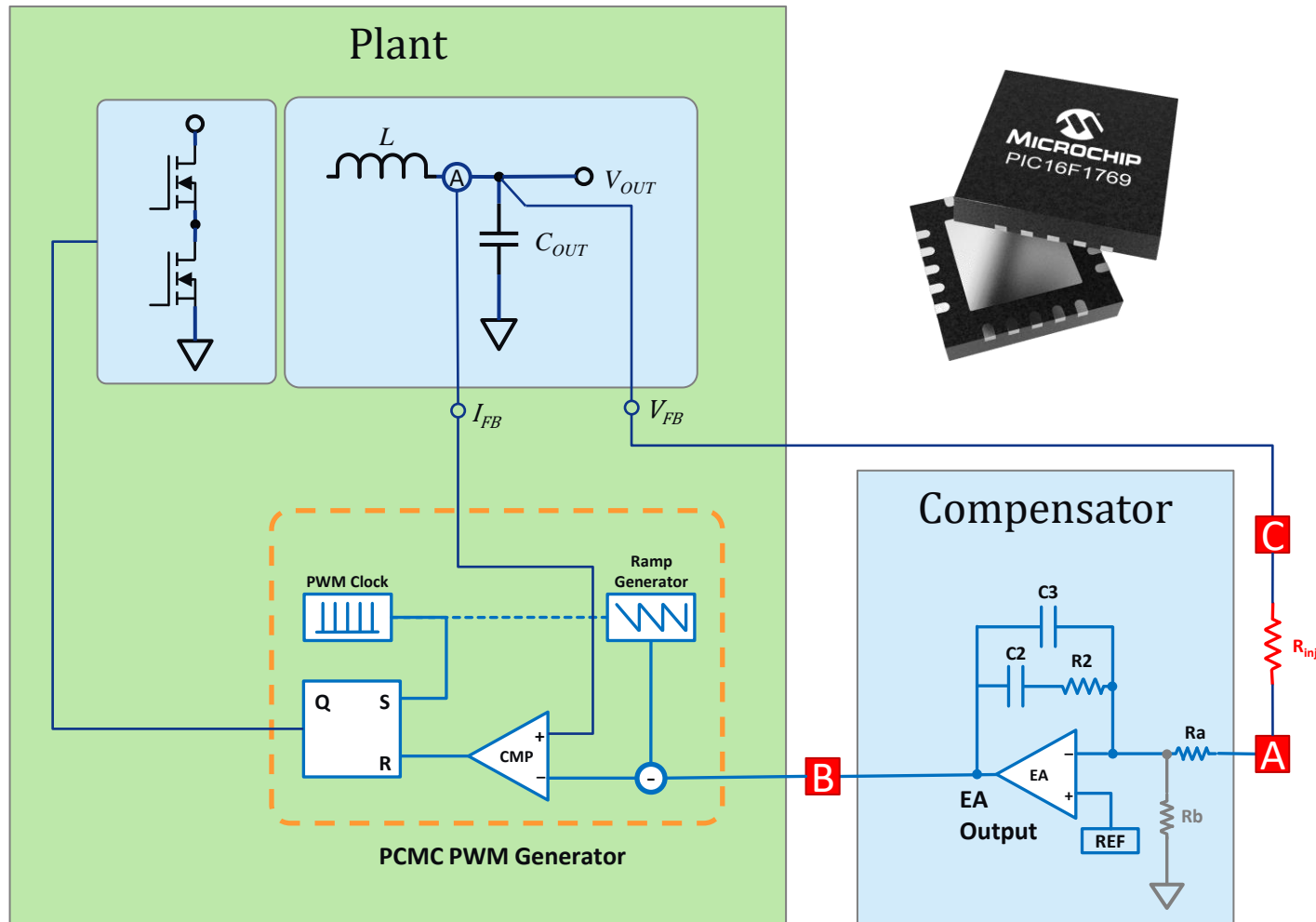
$$G_{OL}(s) = G(s) \times H(s)$$



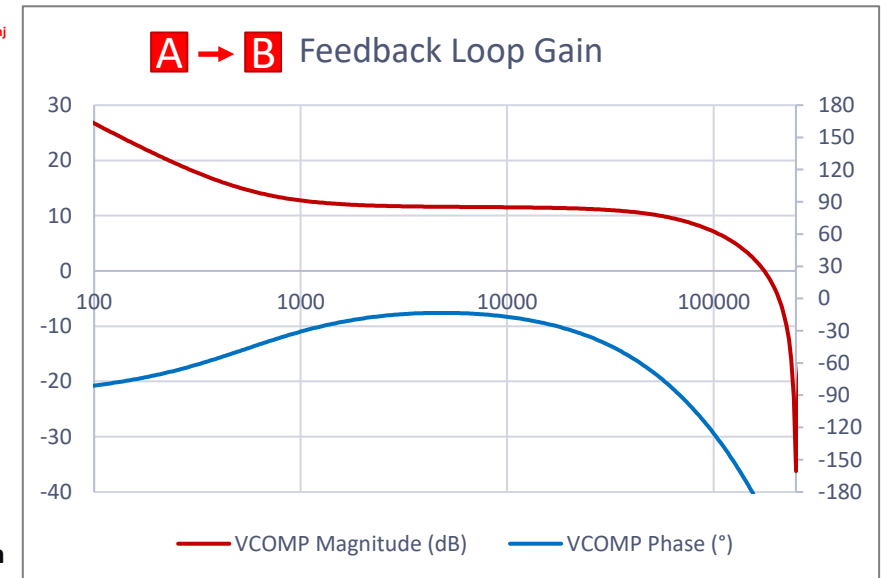
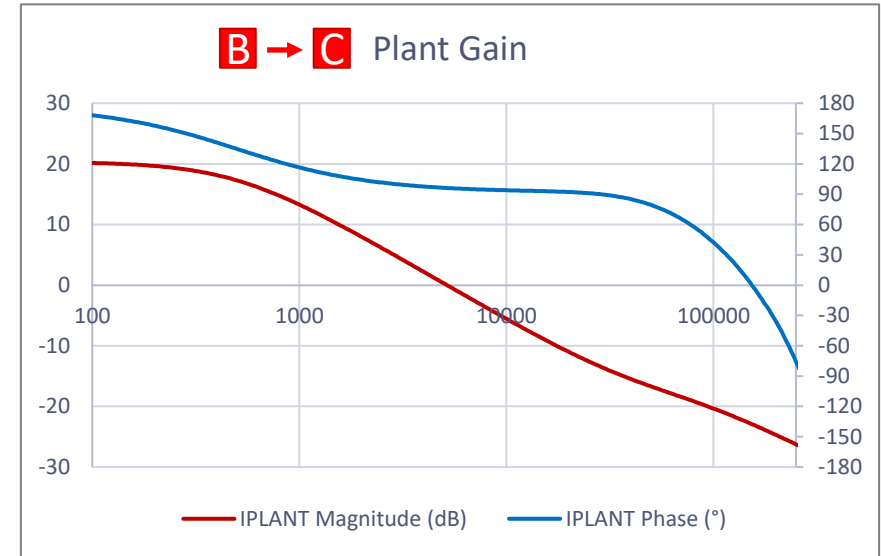
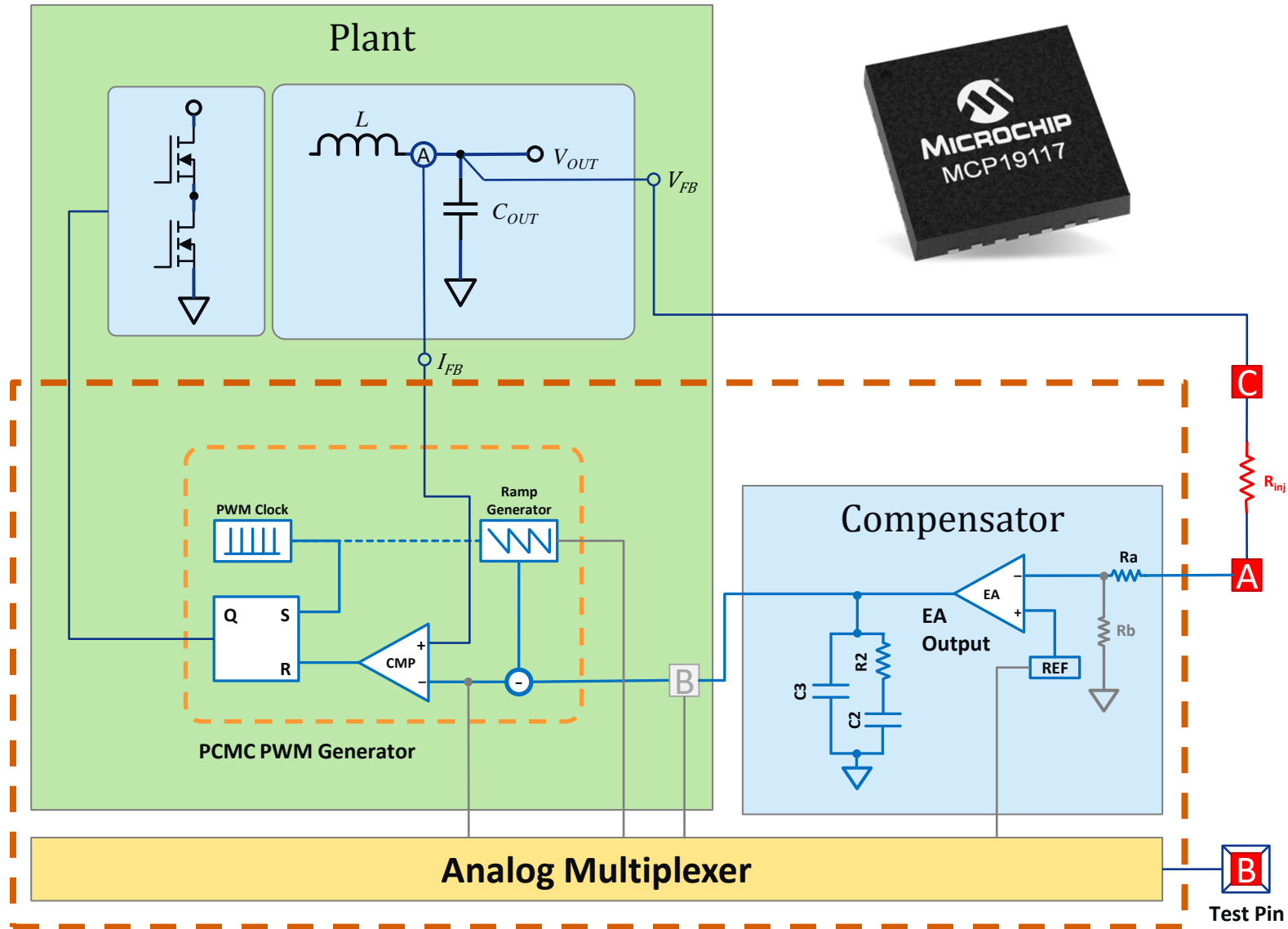
$\Delta V_{CH1-CH2} \text{ MAX} \approx 4 \text{ V}$

- A ✓
- B !
- C !

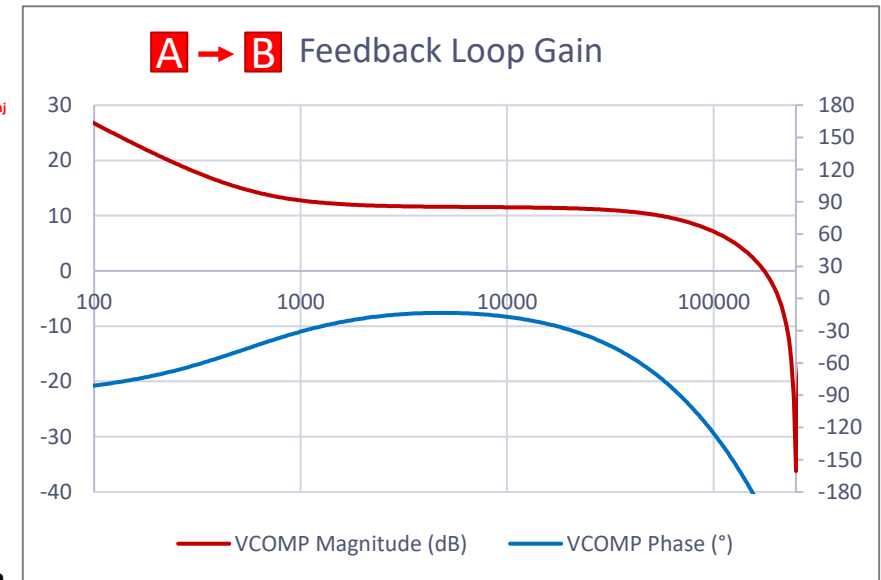
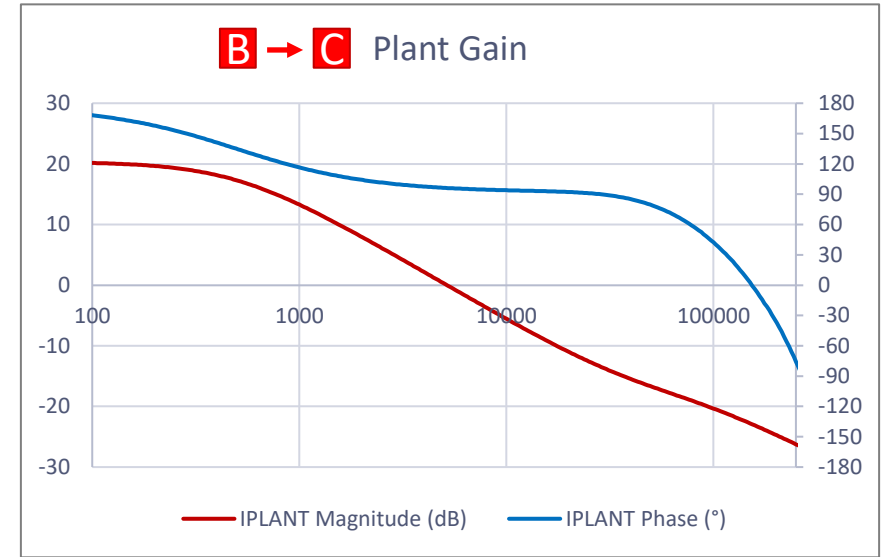
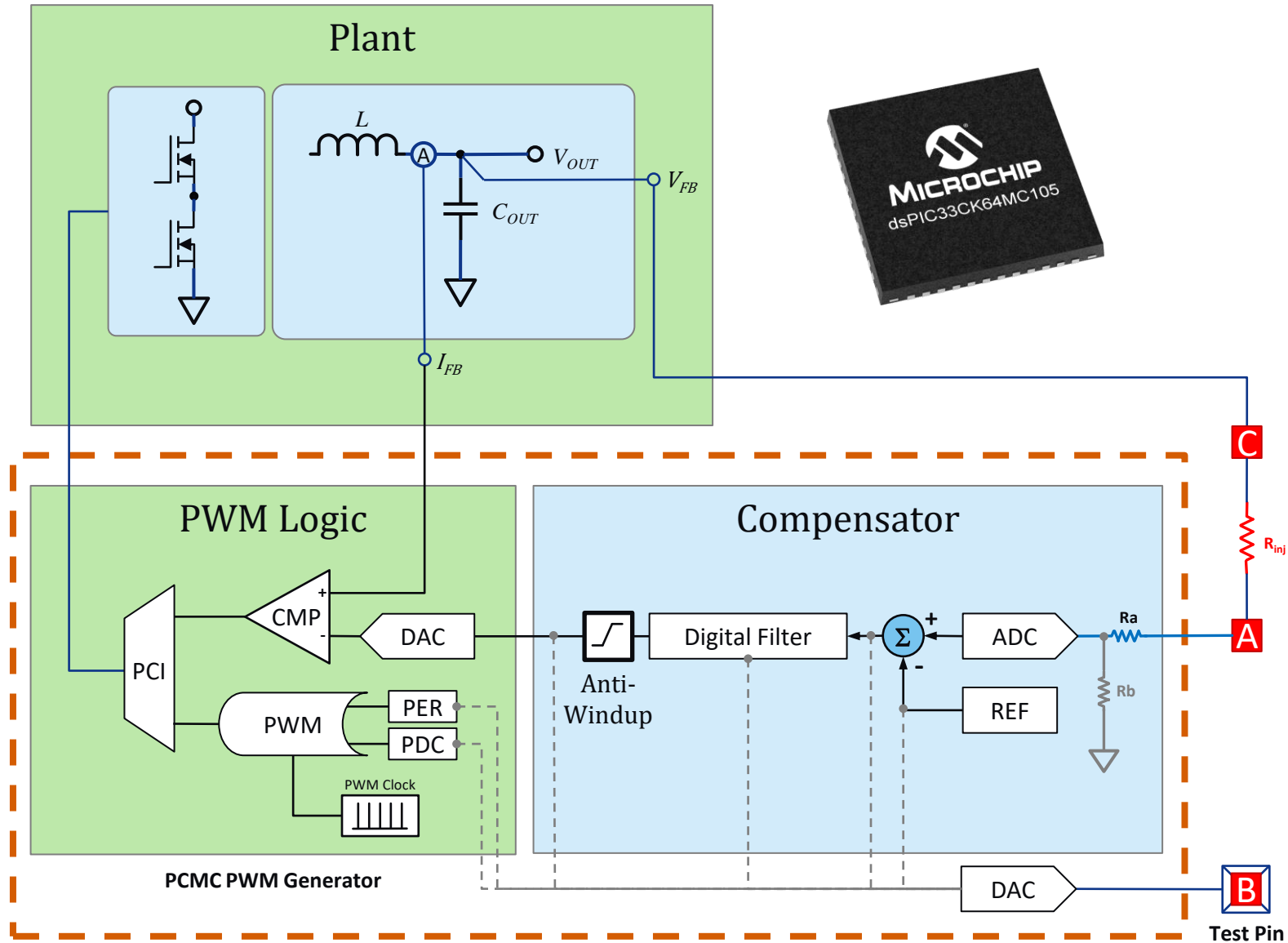
Analog PWM Controller Access Points



Programmable Analog PWM Controller Access Points



Digital PWM Controller Access Points

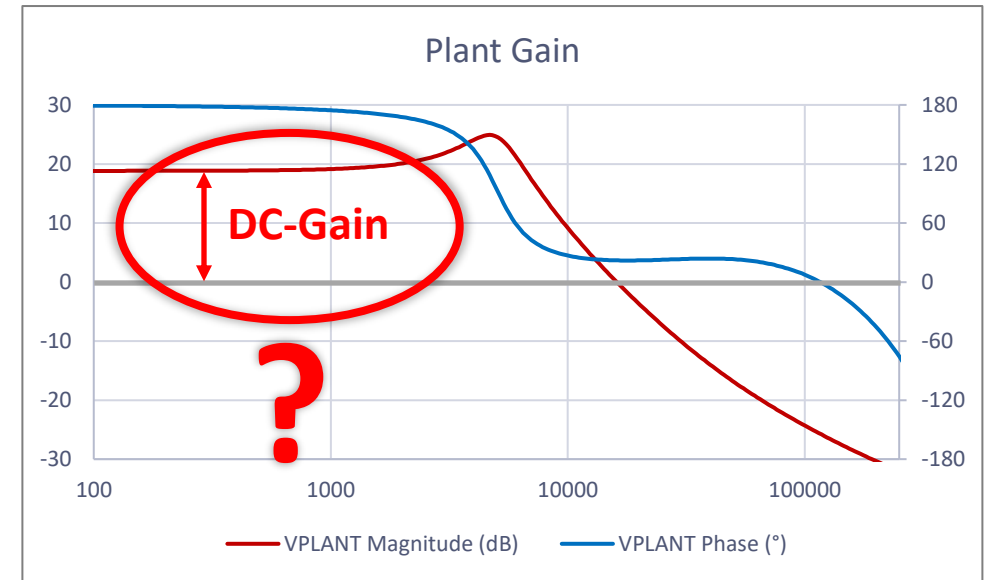
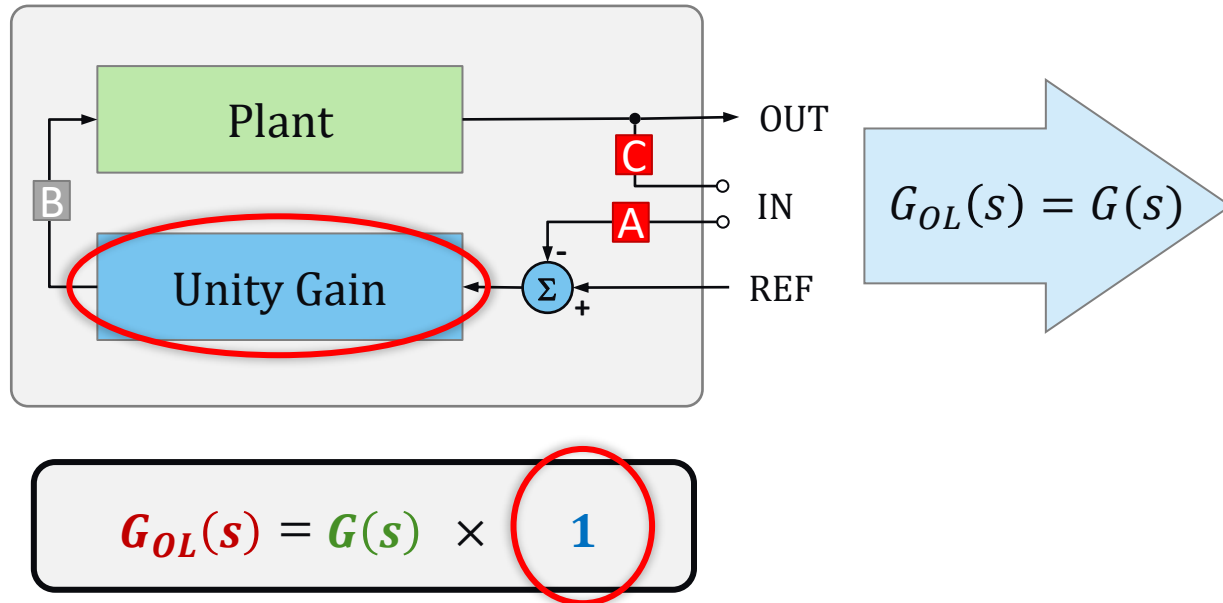


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Constant Gain Feedback Loop



- Method proposed by Ali Shirsavar in 2010:
 - With an effective compensator gain of =1, the remaining, observable response is produced by the plant transfer function
 - Challenge:
 - *How to properly represent the DC Gain component?*
 - *Solution: Operating board close to nominal conditions*

Constant Gain Feedback Loop

Unity Gain Loop (Proportional Controller):

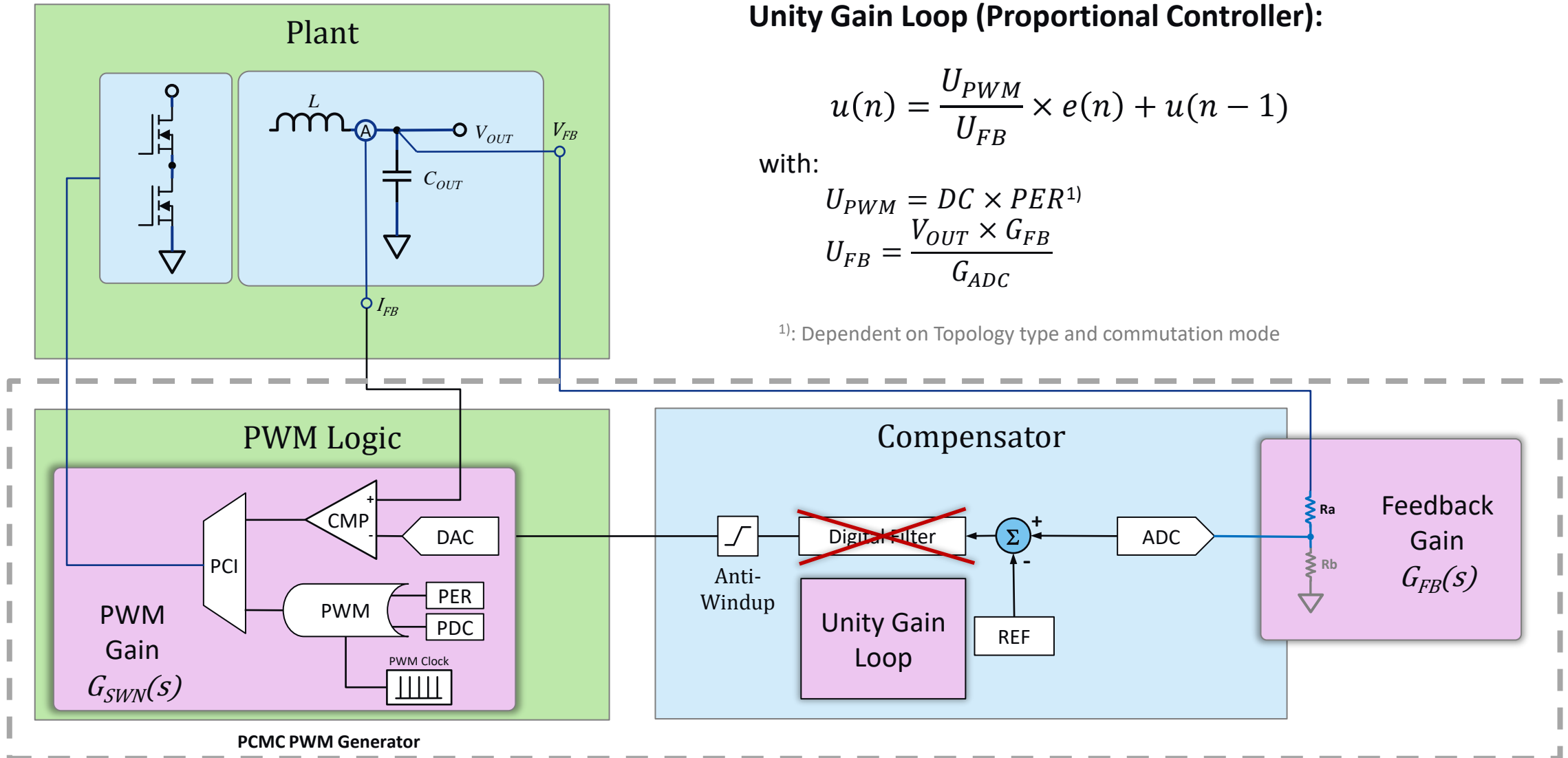
$$u(n) = \frac{U_{PWM}}{U_{FB}} \times e(n) + u(n - 1)$$

with:

$$U_{PWM} = DC \times PER^{1)}$$

$$U_{FB} = \frac{V_{OUT} \times G_{FB}}{G_{ADC}}$$

¹⁾: Dependent on Topology type and commutation mode



Example: Deriving Boost Converter Parameters

$$u(n) = \frac{U_{PWM}}{U_{FB}} \times e(n) + u(n-1)$$
$$u(n) = k \times e(n) + u(n-1)$$

1. $U_{PWM} = DC \times PER = 3,556 \text{ ticks}$

1.1 $DC = \frac{1}{\eta} \times \left(1 - \frac{V_{IN}}{V_{OUT}}\right) = \frac{1}{0.9} \times \left(1 - \frac{9V}{15V}\right) = 44\%$

1.2 $PER = \frac{f_{PCLK}}{f_{sw}} = \frac{4 \text{ GHz}}{500 \text{ kHz}} = 8,000 \text{ ticks}$

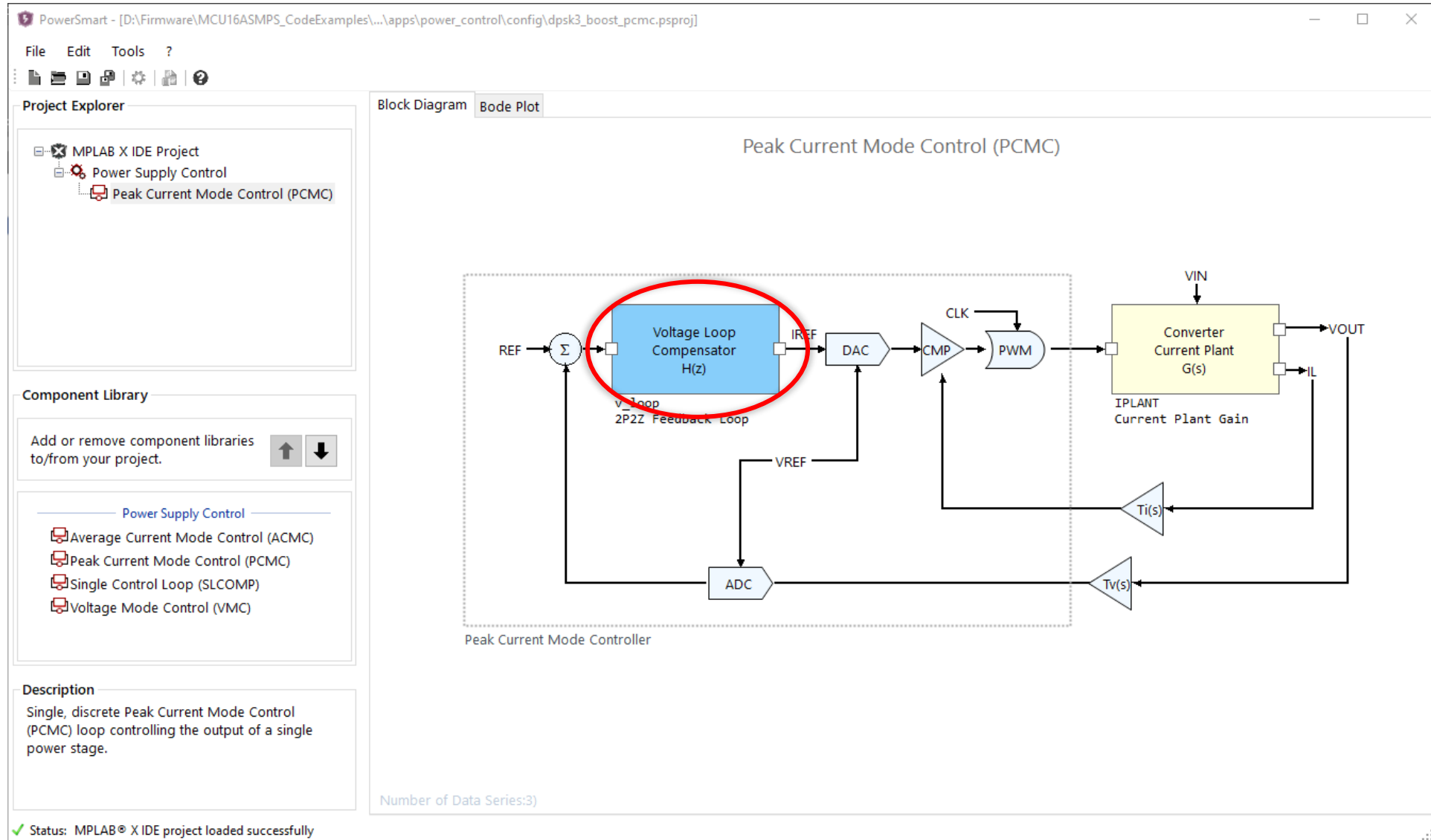
2. $U_{FB} = V_{OUT} \times \frac{G_{FB}}{G_{ADC}} = 15 \text{ V} \times \frac{0.125 \frac{V}{V}}{805.7 \times 10^{-6} \frac{V}{\text{tick}}}$
 $= 2,333 \text{ ticks}$

2.1 $G_{FB} = \frac{R_a}{R_a + R_b} = \frac{6.98 \text{ k}\Omega}{6.98 \text{ k}\Omega + 1.0 \text{ k}\Omega} = 0.125 \frac{V}{V}$

2.2 $G_{ADC} = \frac{V_{REF}}{ADC_{max}} = \frac{3.3 \text{ V}}{4,096} = 805.7 \times 10^{-6} \frac{V}{\text{tick}}$

$$k = \frac{U_{PWM}}{U_{FB}} = \frac{3,556 \text{ ticks}}{2,333 \text{ ticks}} = 1.524027$$

Deriving Parameters using MPLAB® PowerSmart™



Deriving Parameters using MPLAB® PowerSmart™

The screenshot shows the MPLAB PowerSmart Digital Control Library Designer interface. A red circle highlights the 'Use P-Term Loop Controller for Plant Measurements' checkbox and its associated fields: Nominal Feedback Level (2334), Nominal Control Output (3555), Fractional (0.76153564453125), and Scaler (-1). A red arrow points from this area to the 'Nominal Feedback Level Calculator' dialog box.

The dialog box is titled 'Nominal Feedback Level Calculator' and has tabs for 'Voltage Feedback', 'Shunt Amplifier', 'Current Transformer', and 'Digital Source'. The 'Voltage Feedback' tab is active, showing a circuit diagram of a voltage feedback amplifier with an ADC. The circuit includes an input voltage V_{IN} , resistors R_1 and R_2 , an amplifier G_{AMP} , and an output voltage V_{OUT} connected to an ADC.

The dialog box contains the following input and calculation fields:

Field	Value
ADC Reference	3.3 V
ADC Resolution	12 Bit
Minimum	0
Maximum	4095
Differential (signed)	<input type="checkbox"/>
Nominal Sense Voltage	15.006 V
R1	6.98k Ω
R2	1.0k Ω
Amplifier Gain	1.000 V/V
Signal Gain	0.125313 V/V

The dialog box also includes a 'Bode Plot Settings' panel on the right with the following settings:

Category	Parameter	Value
Frequency	Start	100 Hz
	Stop	250k Hz
	Points	801
Magnitude/Gain	Min	-60 dB
	Max	60 dB
	Div	20 dB
	Phase	Min: -180 °
	Max: 180 °	
	Div: 30 °	
Options	Unwrap Phase	<input checked="" type="checkbox"/>
	Show s-Domain	<input checked="" type="checkbox"/>

At the bottom of the dialog box, there is a table with the following data:

Error	Int	UInt
0.001%	31,256	31,256
-0.002%	-29,743	35,793
0.003%	26,509	26,509
0.003%	27,957	27,957
-0.003%	-26,480	39,056

The dialog box has 'OK' and 'Cancel' buttons at the bottom.

Deriving Parameters using MPLAB® PowerSmart™

The screenshot shows the MPLAB PowerSmart Digital Control Library Designer interface. A red circle highlights the 'Use P-Term Loop Controller for Plant Measurements' checkbox and its associated fields: Nominal Feedback Level (2334), Nominal Control Output (3555), Fractional (0.76153564453125), and Scaler (-1). A red arrow points from this area to the 'Nominal Ouput Level Calculator' dialog.

The 'Nominal Ouput Level Calculator' dialog is open, showing a graph of the PWM signal. The graph plots PWM Signal against Time t . The signal is a square wave with a period T_{PWM} . The duty cycle is defined by D (the high time) and D' (the low time).

The 'Nominal Control Output Calculator' dialog is also open, showing the following parameters:

- Converter Type: 1 - Boost Converter
- Winding Ratio (P/S): 1 : 1
- Nominal Input Voltage: 9.0 V
- Nominal Output Voltage: 15.006 V
- Nominal Efficiency: 90.0 %
- Nominal Duty Ratio: 44.469995 %

The 'Calculation' section of the dialog shows the following values:

- PWM Frequency: 500.0k Hz
- PWM Period: 2.0u sec
- PWM Period Count: 8000 ticks
- Effective Resolution: 12.966 bit
- Nominal Duty Ratio: 44.47 %
- Signal Gain: 0.122072 tick/tick

A red arrow points from the 'Nominal Duty Ratio' field in the 'Calculation' section to the 'Nominal Duty Ratio' field in the 'Nominal Control Output' section.

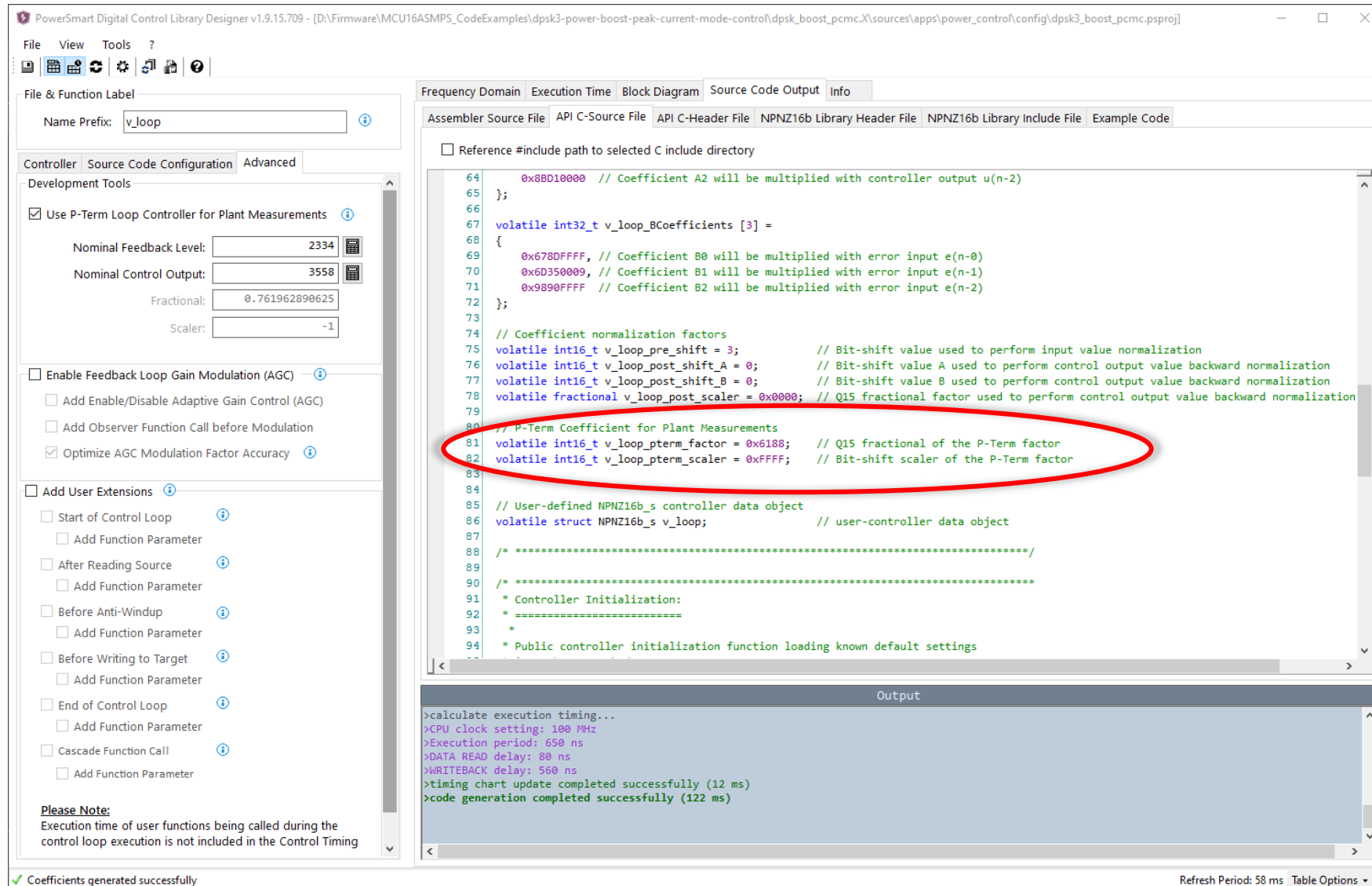
Deriving Parameters using MPLAB® PowerSmart™

The screenshot displays the MPLAB PowerSmart Digital Control Library Designer interface. The 'Advanced' tab is selected, showing the 'Development Tools' section. A red circle highlights the 'Fractional' parameter value of 0.761962890625. Below this, a table titled 'Filter Coefficients' provides detailed numerical data for the controller's coefficients.

Coefficient	Float	Bsft-Scaler	Scaled Float	Fractional	FP Error	Int	UInt
A-Coefficients							
A1	1.907704262668930	-1	0.953852131334466	0.953857421875000	0.001%	31,256	31,256
A2	-0.907704262668931	0	-0.907704262668931	-0.907684326171875	-0.002%	-29,743	35,793
B-Coefficients							
B0	1.617929806295270	-1	0.808964903147637	0.808990478515625	0.003%	26,509	26,509
B1	0.001666324931139	9	0.853158364743289	0.853179931640625	0.003%	27,957	27,957
B2	-1.616263481364140	-1	-0.808131740682068	-0.808105468750000	-0.003%	-26,480	39,056

<https://www.microchip.com/PowerSmart>

Deriving Parameters using MPLAB® PowerSmart™



PowerSmart Digital Control Library Designer v1.9.15.709 - [D:\Firmware\MCU16ASMP5_CodeExamples\dpsk3-power-boost-peak-current-mode-control\dpsk_boost_pcmc.X\sources\apps\power_control\config\dpsk3_boost_pcmc.psproj]

File View Tools ?

File & Function Label
Name Prefix: v_loop

Controller Source Code Configuration Advanced

Development Tools

Use P-Term Loop Controller for Plant Measurements

Nominal Feedback Level: 2334

Nominal Control Output: 3558

Fractional: 0.761962890625

Scaler: -1

Enable Feedback Loop Gain Modulation (AGC)

Add Enable/Disable Adaptive Gain Control (AGC)

Add Observer Function Call before Modulation

Optimize AGC Modulation Factor Accuracy

Add User Extensions

Start of Control Loop

Add Function Parameter

After Reading Source

Add Function Parameter

Before Anti-Windup

Add Function Parameter

Before Writing to Target

Add Function Parameter

End of Control Loop

Add Function Parameter

Cascade Function Call

Add Function Parameter

Please Note:
Execution time of user functions being called during the control loop execution is not included in the Control Timing

Frequency Domain Execution Time Block Diagram Source Code Output Info

Assembler Source File API C-Source File API C-Header File NPNZ16b Library Header File NPNZ16b Library Include File Example Code

Reference #include path to selected C include directory

```
64     0x8BD10000 // Coefficient A2 will be multiplied with controller output u(n-2)
65 };
66
67 volatile int32_t v_loop_BCoefficients [3] =
68 {
69     0x678DFFFF, // Coefficient B0 will be multiplied with error input e(n-0)
70     0x6D350009, // Coefficient B1 will be multiplied with error input e(n-1)
71     0x9890FFFF, // Coefficient B2 will be multiplied with error input e(n-2)
72 };
73
74 // Coefficient normalization factors
75 volatile int16_t v_loop_pre_shift = 3; // Bit-shift value used to perform input value normalization
76 volatile int16_t v_loop_post_shift_A = 0; // Bit-shift value A used to perform control output value backward normalization
77 volatile int16_t v_loop_post_shift_B = 0; // Bit-shift value B used to perform control output value backward normalization
78 volatile fractional v_loop_post_scaler = 0x0000; // Q15 fractional factor used to perform control output value backward normalization
79
80 // P-Term Coefficient for Plant Measurements
81 volatile int16_t v_loop_pterm_factor = 0x6188; // Q15 fractional of the P-Term factor
82 volatile int16_t v_loop_pterm_scaler = 0xFFFF; // Bit-shift scaler of the P-Term factor
83
84
85 // User-defined NPNZ16b_s controller data object
86 volatile struct NPNZ16b_s v_loop; // user-controller data object
87
88 /*
89
90
91
92
93
94
95
96
97
98
99
100
101
102
103
104
105
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107
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Output

```
>calculate execution timing...
>CPU clock setting: 100 MHz
>Execution period: 650 ns
>DATA READ delay: 80 ns
>WRITEBACK delay: 560 ns
>timing chart update completed successfully (12 ms)
>code generation completed successfully (122 ms)
```

✓ Coefficients generated successfully Refresh Period: 58 ms Table Options

Caution!

- **Unity Gain Loops are not robust control loops!**
- **Measurement requires stable operating conditions**
 - No fast load changes
 - No fast changes in input voltage
- **Vitally require slow soft-start & protection**
 - Loop controller must be embedded in startup state machine
 - Use hardware current limit if possible
 - **Clamp allowed operating range with tight Anti-Windup limits (especially with LLC resonant converters)**

Circuit Simulation



PowerSmart - [D:\Firmware\MCU16ASMP5_CodeExamples\...\apps\power_control\config\dpsk3_boost_vmc.psproj]

File Edit Tools ?

Project Explorer

- MPLAB X IDE Project
- Power Supply Control
- DPSK3 Boost VMC Type III

Block Diagram Bode Plot

DPSK3 Boost VMC Type III

REF → Σ → Voltage Loop Compensator $H(z)$ → PWM → Converter Voltage Plant $G(s)$ → VOUT

ADC → Σ

VIN → Converter Voltage Plant $G(s)$

VREF → ADC

CLK → PWM

CLK → ADC

$T_v(s)$

Voltage Mode Controller

Number of Data Series:3

✓ Status: MPLAB® X IDE project loaded successfully

Circuit Simulation

Plant import from external sources



MPLAB®

POWERSMART™

DEVELOPMENT SUITE

File Import | Simplis/MINDI | Bode Plot


Simplis Schematic File

AC-Analysis Results Import

1 Instructions:
 2 If you do not have any version of Simplis nor MINDI installed on this computer
 3 download a free version of MINDI here: <https://www.microchip.com/MINDI>
 4
 5
 6 If Simplis/MINDI is installed on this computer:
 7
 8 1) Select a Simplis or MINDI simulation schematic file using the 'Browse' but
 9 2) Open the selected simulation schematic in Simplis or MINDI using the 'Open
 10
 11

Add Phase Erosion for Hz Switching Frequency

About MINDI

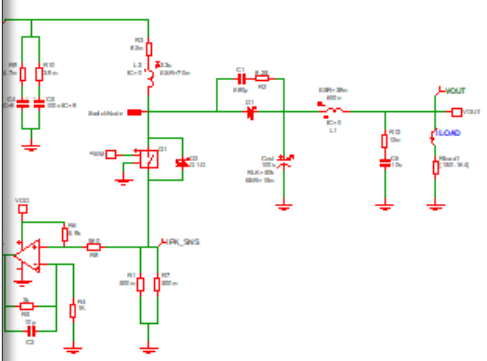


MPLAB® MINDI™ Analog Simulator reduces circuit design time and design risk by
 simulating analog circuits prior to hardware prototyping. The simulation tool
 SIMetrix/SIMPLIS simulation environment, with options to use SPICE or piecewise linear
 modeling, that can cover a very wide set of possible simulation needs. This simulation
 tool installs and runs locally on your PC.

[Download MINDI Analog Simulator](#)

Schematic Editor

File Edit View Simulator Place Probe Probe AC/Noise Hierarchy Monte

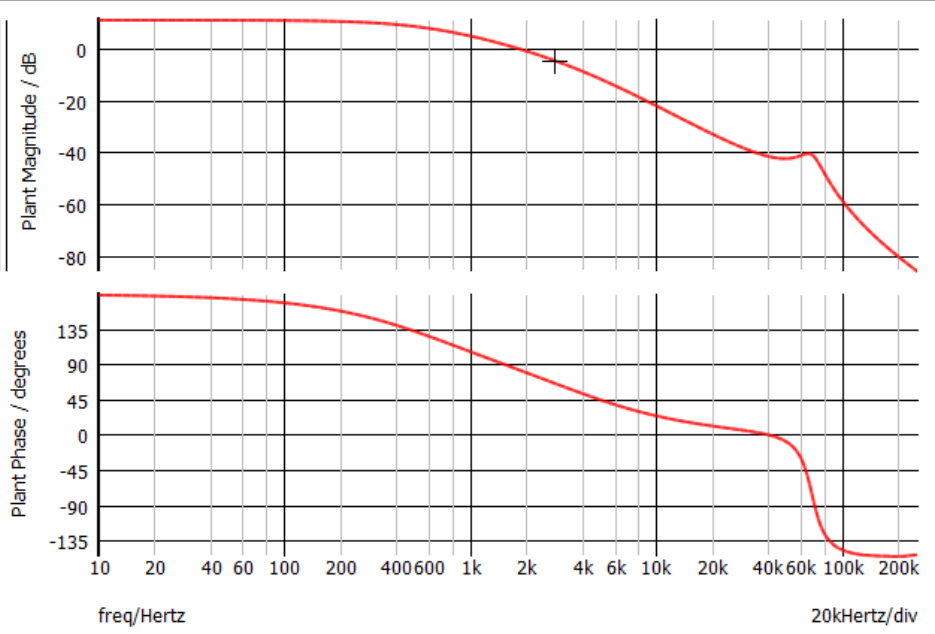


NET = #VCTRL

Waveform Viewer

File Edit View SIMetrix Simulator SIMPLIS Simulator Cursors Annotate Curves » Waveform Viewer

simpelis_ac24 (D:\Documents\Microchip\PowerSmart...ower Starter Kit 3\DPSK3_boost_plant_vmc.wxsch)



Label	Legend	Curve label	Name	Value
<input type="checkbox"/> Plant Magnitu...	—	Plant Magnitu...	Gain Crossover Frequency	1.81991
<input type="checkbox"/> Plant Phase (si...	—	Plant Magnitu...	Gain Marqin	***ERR*

X=2.82813k Y=-4.52336 Plant Magnitude (simpelis_ac34)

Circuit Simulation

Simulation matches measurement principle

dsPIC® Unity Gain Loop Model

BOOST_PWM

Edit PTerm Loop Controller : U3

P Term Loop Controller

Voltage Feedback | Control Output

Description
This is a voltage divider gain calculator where the Analog-to-Digital converter reference voltage and resolution as well as upper and lower resistor value can be entered. By entering the nominal output voltage in the marked field this component will calculate the related reference value used by the controller.

Circuit
Use Feedback Circuit: Yes

Input Scaling
ADC Reference: 3.3 V
ADC resolution: 12

Calculation
Nominal Sense Voltage: 15 V
R1: 6.98k ohm
R2: 1k ohm
Amplifier Gain: 1 V/V

Ok | Cancel

dsPIC® Unity Gain Loop Model Configuration Dialog

Company Microchip Technology Inc.		
Title dsPIC33C Digital Power Starter Kit Boost Converter Voltage Mode Plant Model		
Author MCU16 Applications		
Notes dsPIC33C Digital Power Starter Kit introduces and demonstrates the capabilities and features of Microchip's SMPs families of devices. It features on-board dsPIC33CK258MP505 DSC, SMPs power stages, loads, LCD display, USB/UART bridge and programmer/debugger, which eliminates the need for any additional hardware.		
Version M8.4 Date 01/05/1922		

Circuit Simulation

SIMPLIS Simulation does not consider switch-state phase erosion!



MPLAB POWERSMART DEVELOPMENT SUITE

MINDI Bode Plot

Data Series Name: VPLANT

Project: ... \Examples\Simplis-Mindi\Digital Power Starter Kit 3\DPSK3_boost_plant_vmc.wxsch

AC-Analysis Results Import

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Add Phase Erosion for 500k Hz Switching Frequency

About MINDI

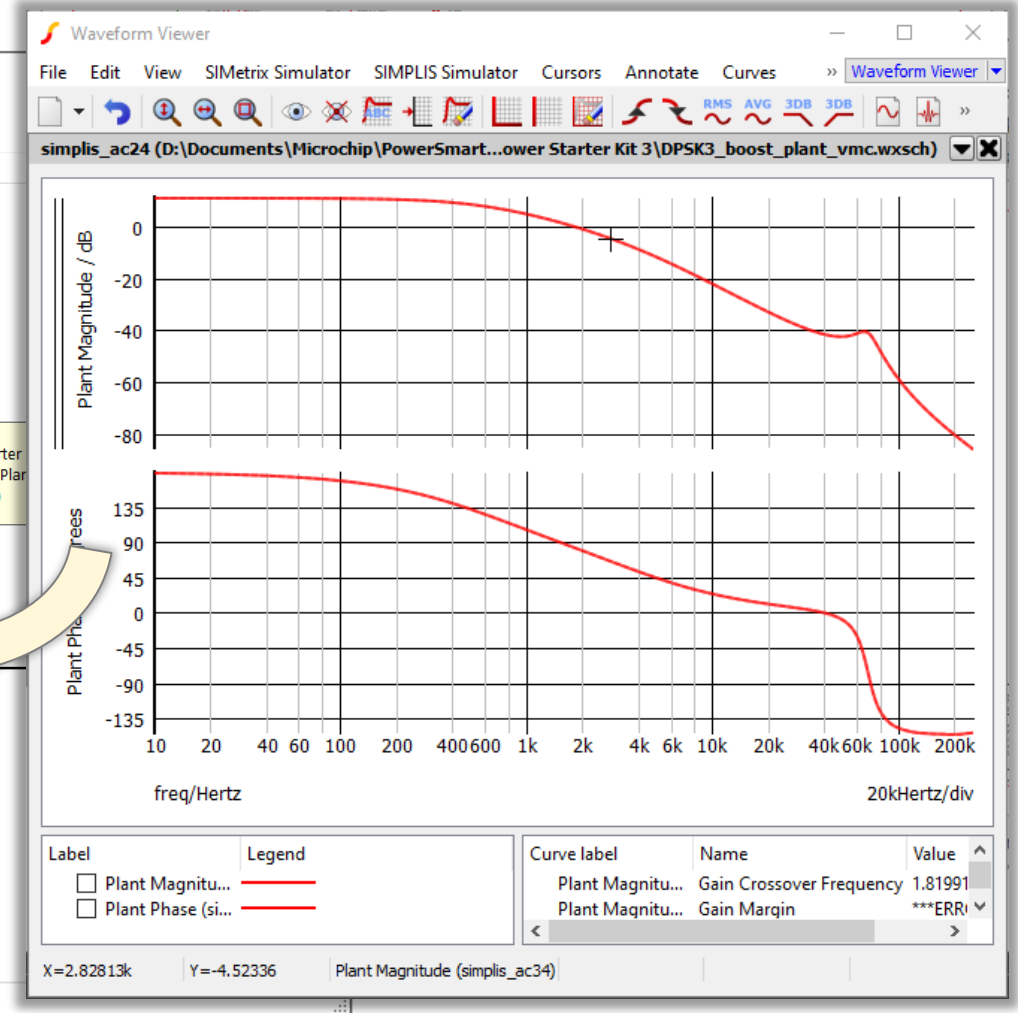
MPLAB MINDI ANALOG SIMULATOR

MPLAB® Mindi™ Analog Simulator reduces circuit design time and design risk by simulating analog circuits prior to hardware prototyping. The simulation tool uses a SIMetrix/SIMPLIS simulation environment, with options to use SPICE or piecewise linear modeling, that can cover a very wide set of possible simulation needs. This simulation tool installs and runs locally on your PC.

[Download MINDI Analog Simulator](#)

Number of Data Series:3

Status: MPLAB® X IDE project loaded successfully



Circuit Simulation



PowerSmart - [D:\Firmware\MCU16ASMPS_CodeExamples\...\apps\power_control\config\dpsk3_boost_vmc.psproj]

File Edit Tools ?

Project Explorer

- MPLAB X IDE Project
 - Power Supply Control
 - DPSK3 Boost VMC Type III

Component Library

Add or remove component libraries to/from your project.

- Power Supply Control
 - Average Current Mode Control (ACMC)
 - Peak Current Mode Control (PCMC)
 - Single Control Loop (SLCOMP)
 - Voltage Mode Control (VMC)

Description

Single, discrete Voltage Mode Control (VMC) loop controlling the output of a single power stage.

Block Diagram Bode Plot

Frequency: 1.815k Hz | Magnitude: 0.0 dB | Phase: 82.1 °

Magnitude [dB]

Phase [°]

Frequency [Hz]

VPLANT (Mag) VPLANT (Phase)

Bode Plot Settings

Frequency

Start: 10 Hz

Stop: 100k Hz

Points: 401

Magnitude/Gain

Min: -60 dB

Max: 60 dB

Div: 10 dB

Phase

Min: -180 °

Max: 180 °

Div: 30 °

Focus Series

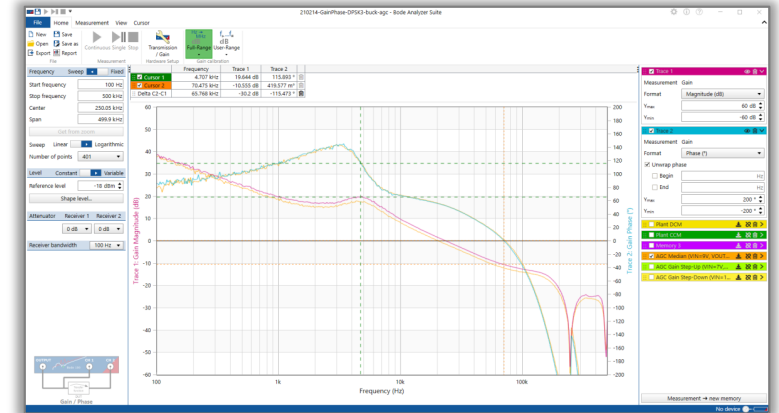
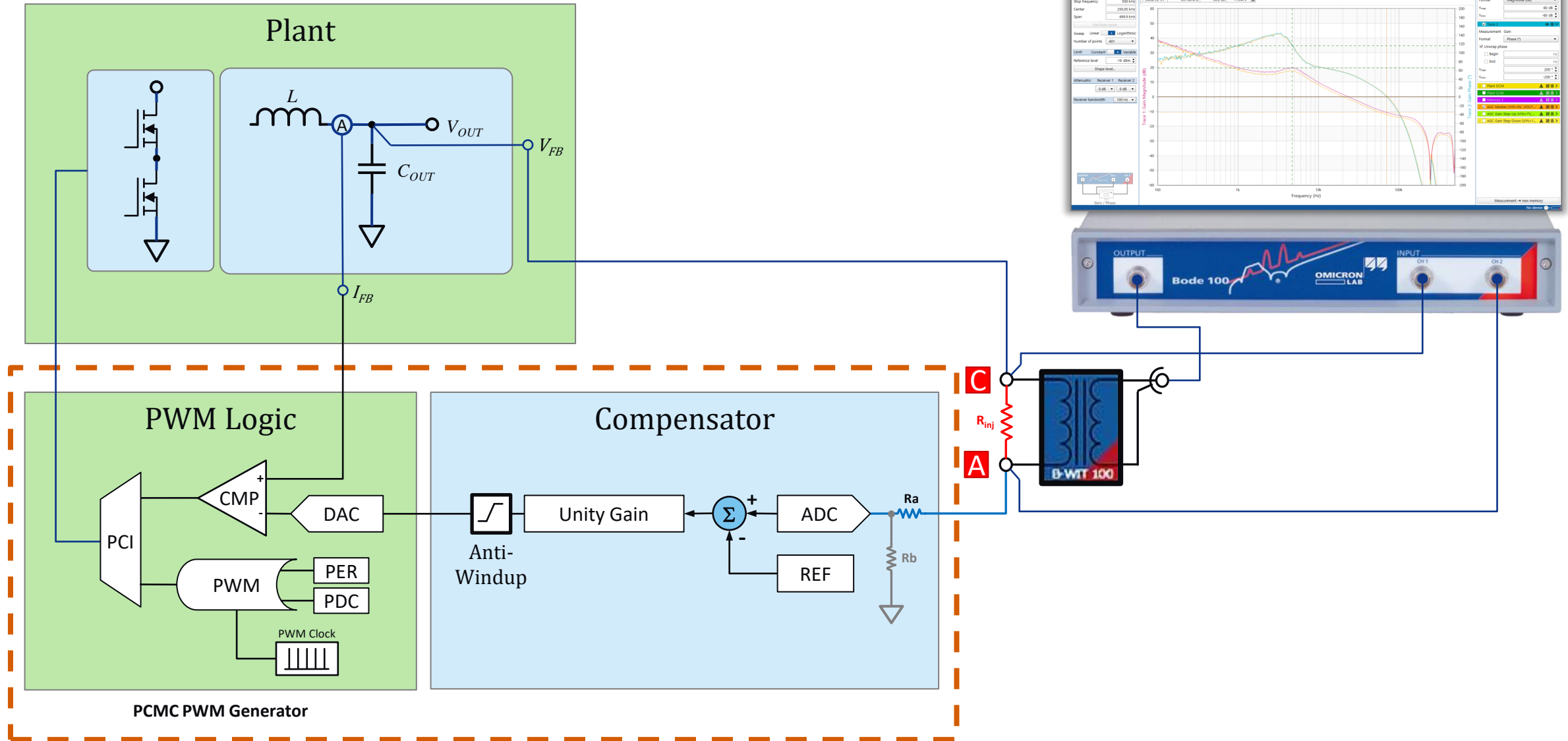
Plant Gain

Show/Hide Data Series

- Plant Gain
- 3P3Z Feedback Loop
- Open Loop Gain

Status: MPLAB® X IDE project loaded successfully

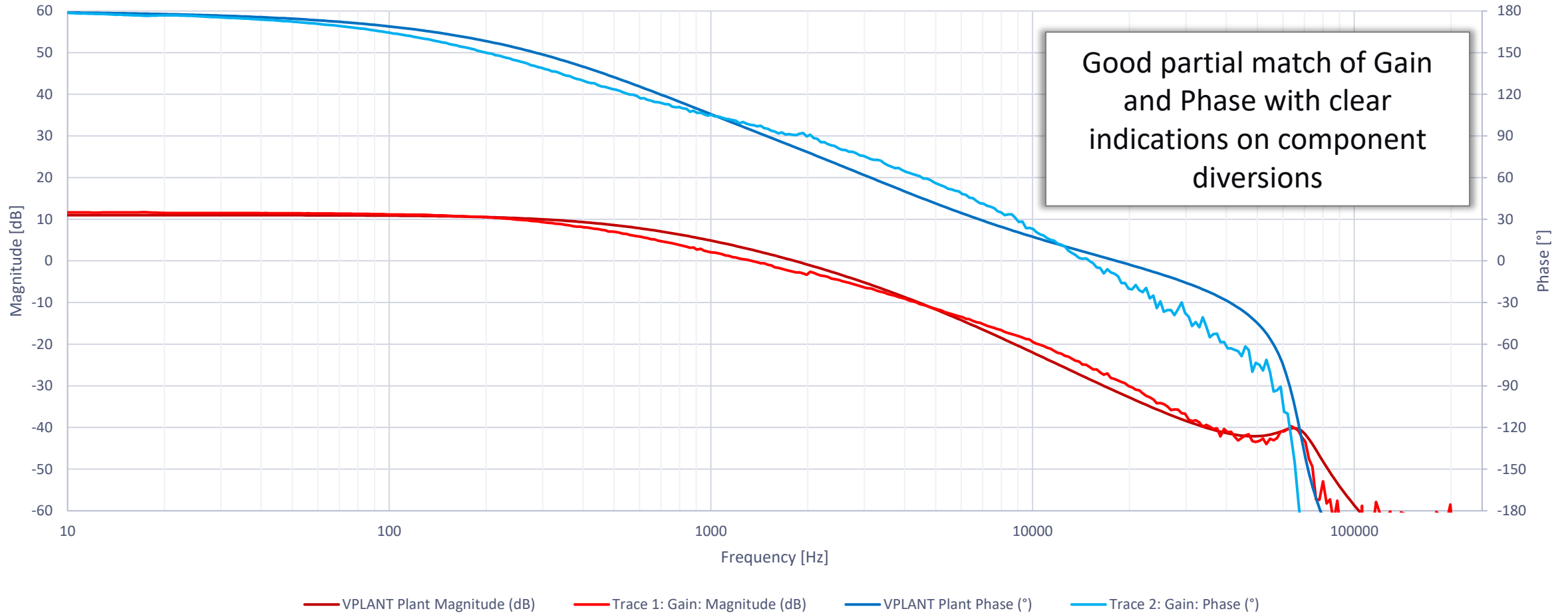
Measurement Setup



Initial Test Results

Simplis Simulation vs. Bench Measurement

DPSK3 Boost Converter Plant Gain (Voltage Mode)

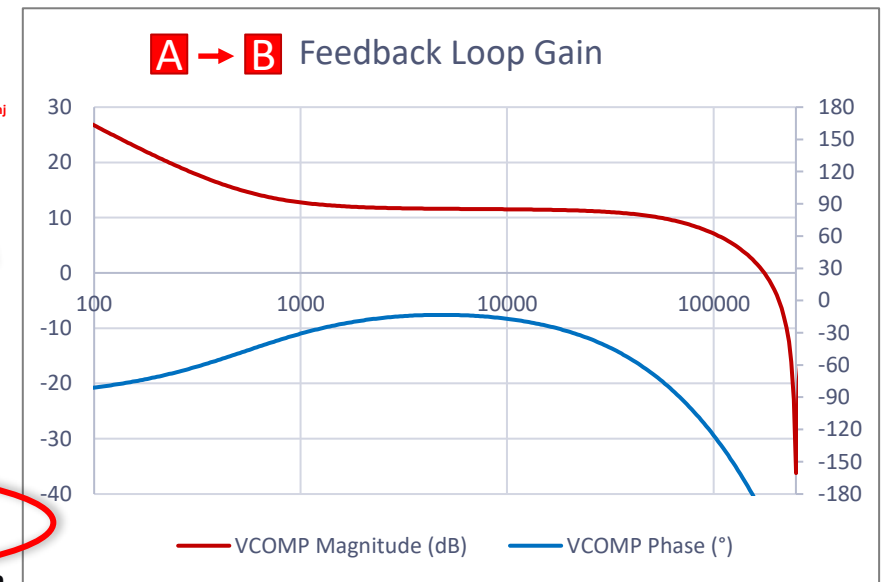
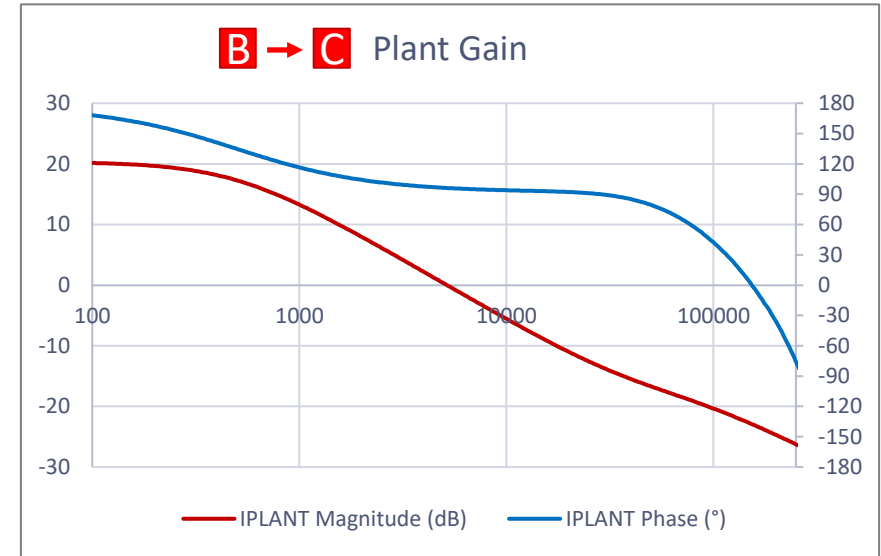
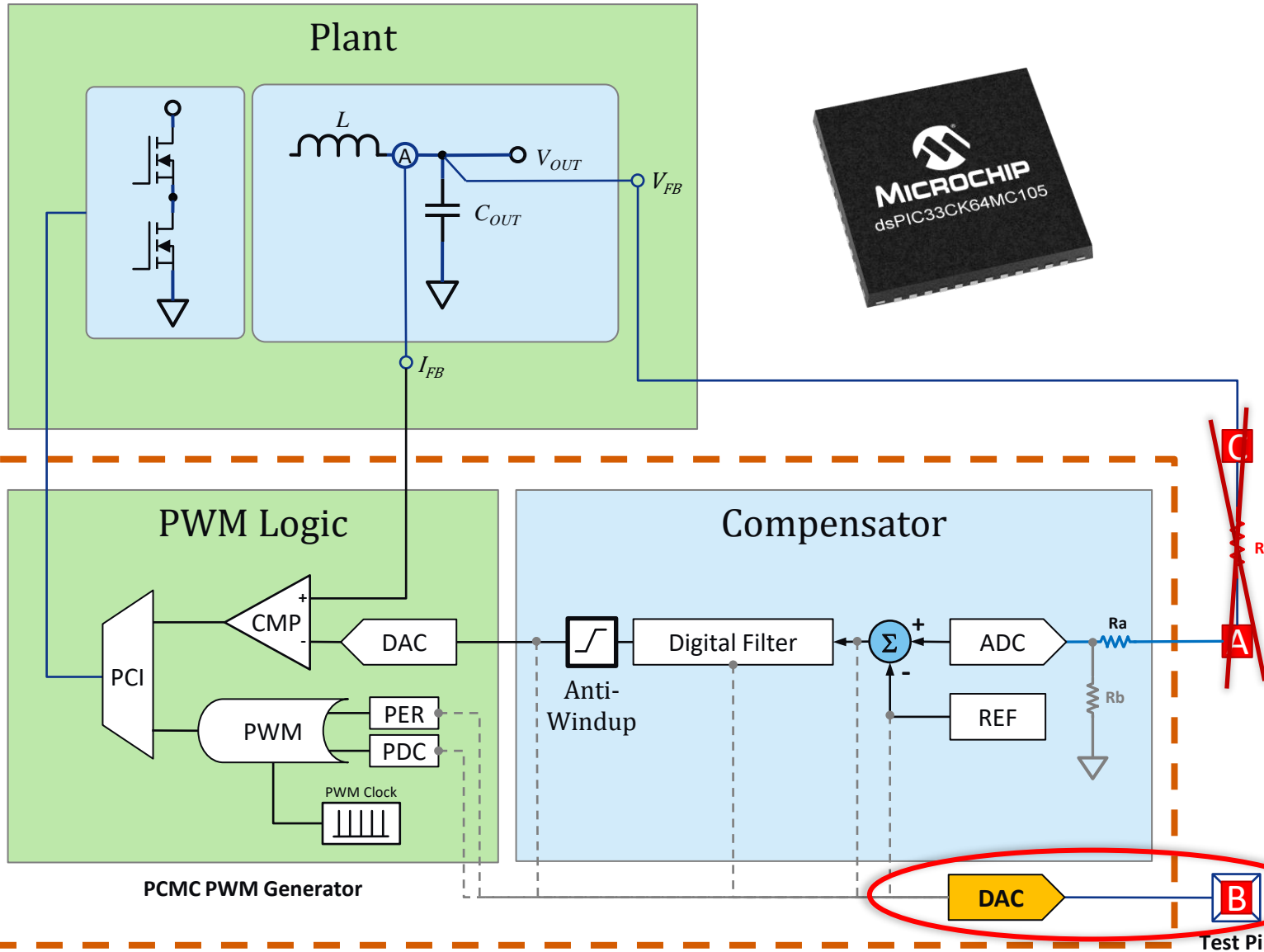


Agenda

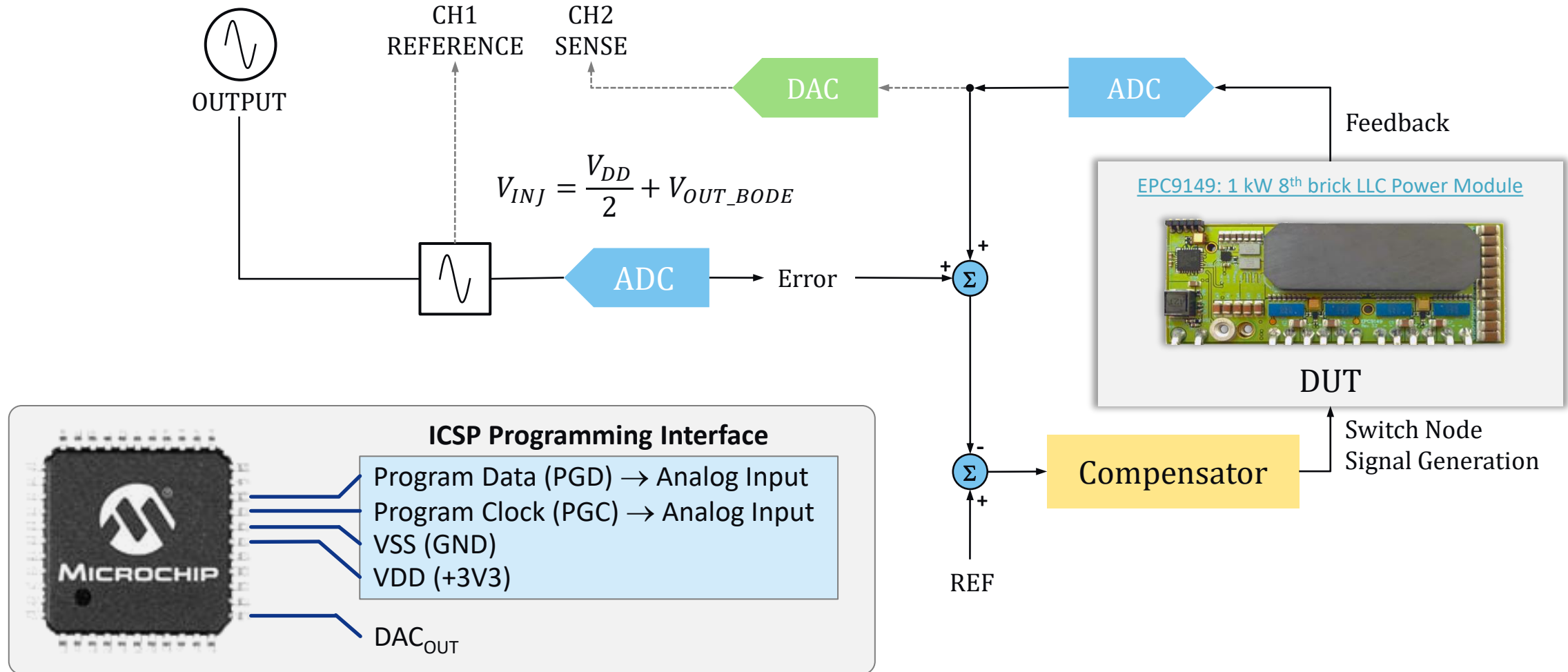
- System Modelling Challenges
- Frequency Domain Design: The Basics
- **Plant Frequency Response Measurements**
 - Constant Gain Feedback Loop
 - Digitally Decoupled Injection (non-invasive)
- Summary

- Appendix:
 - In-Chip Measurement

Digital PWM Controller Access Points



Reusing Available Pins (+1)



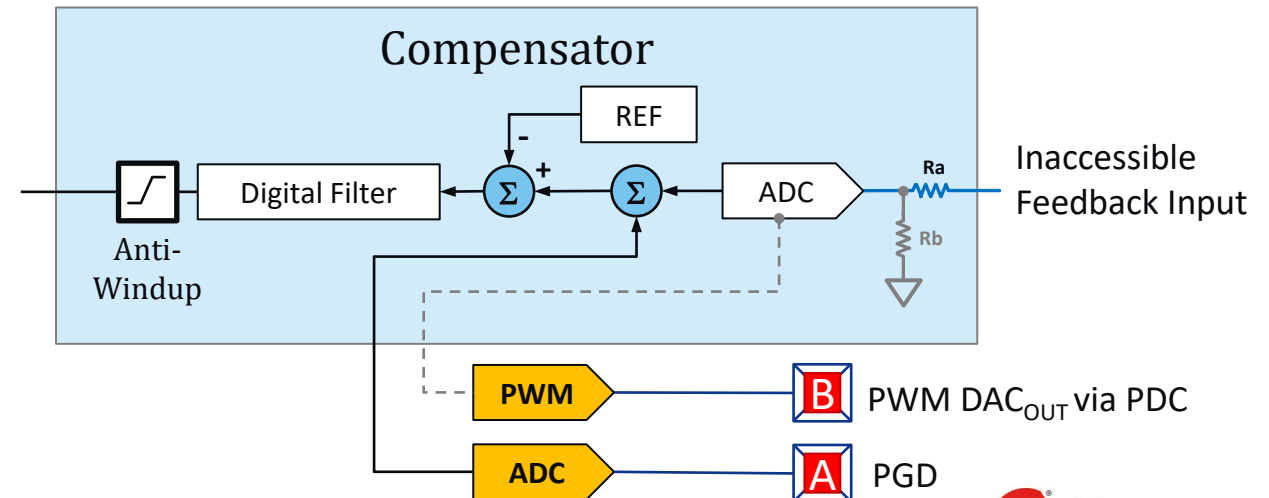
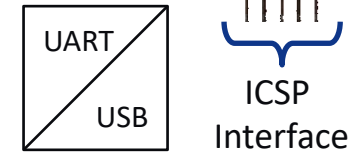
Loop Injection through ICSP

- PWM Channels can be internally routed to any GPIO
- Configuring PWM channel with 1 MHz PWM Frequency, provides high speed response with 12-bit resolution (equivalent to analog DAC)
- Analog filtering of PWM output is not required as Bode 100 filters low-voltage/high frequency signal automatically (!!!)

[EPC9151 300W 16th Brick Power Module on EPC9531 Test Fixture Board](#)

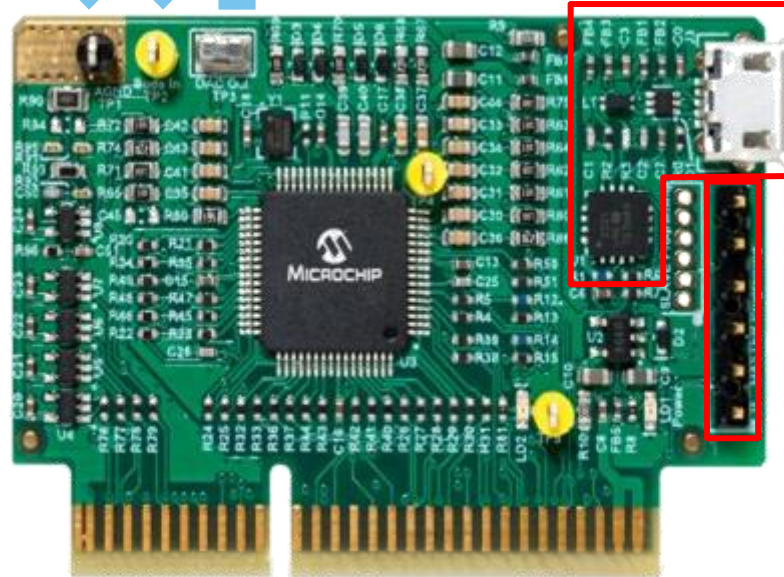


No DAC Output !!!



Default Option on CPU Plug-In Boards

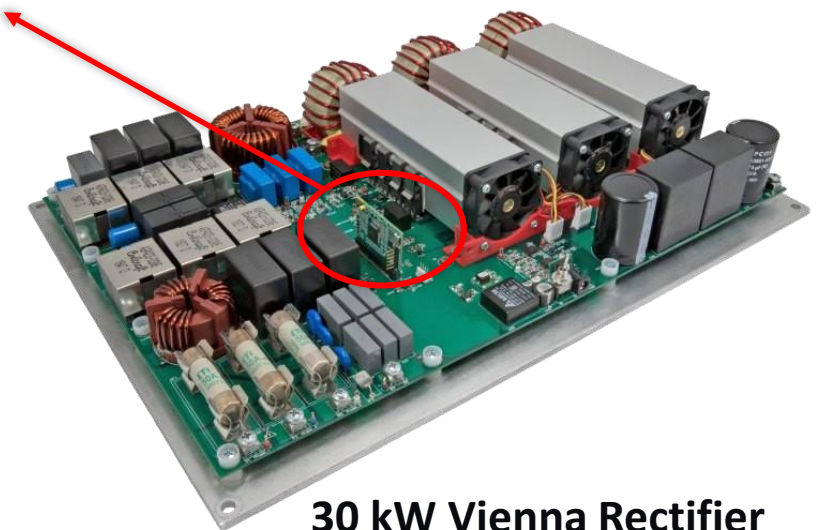
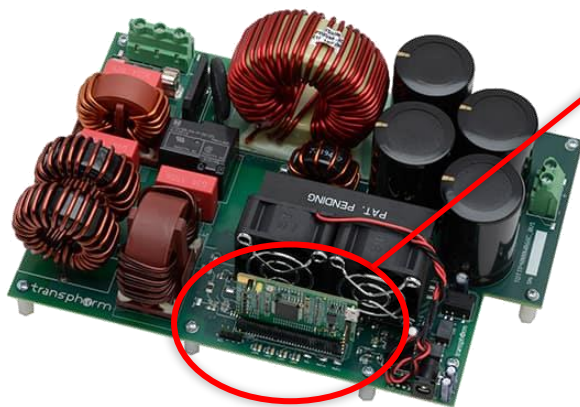
- 1 VSS (GND)
- 2 ADC Injection Point
- 3 DAC Output



ICSP Programming Interface

Analog I/O Digital I/O

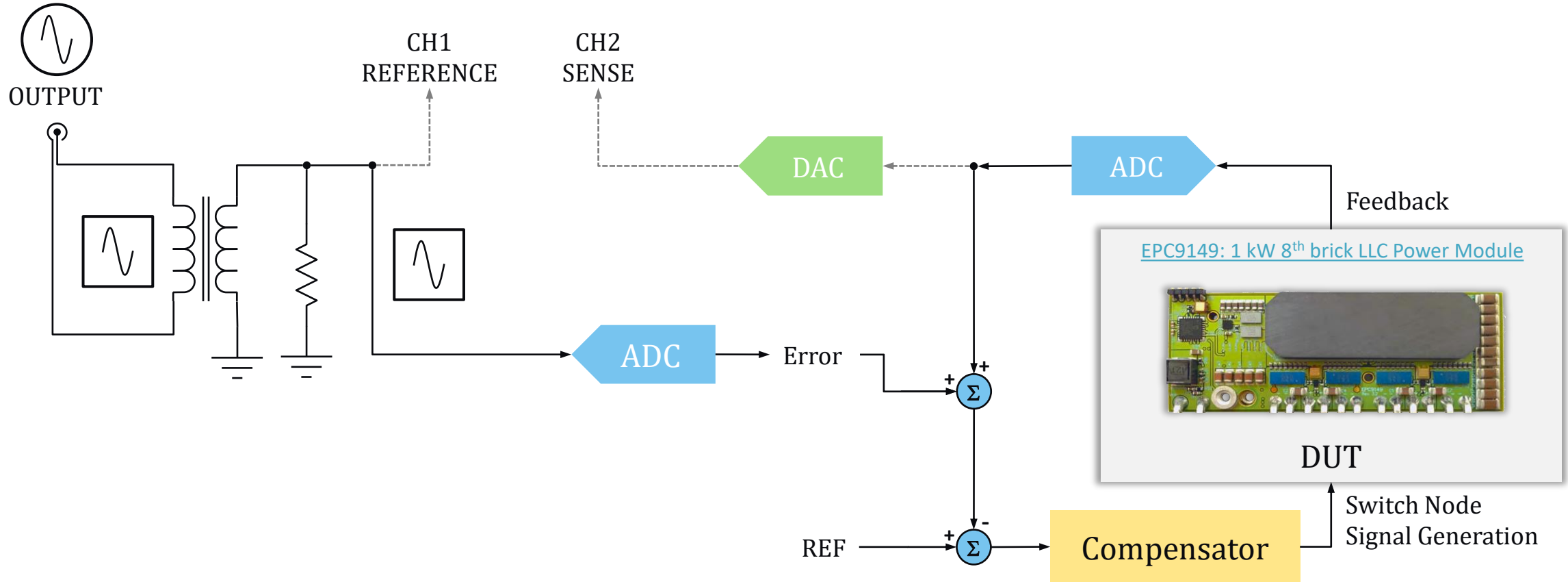
2.5 kW and 4 kW TTP PFC
Transphorm GaN Reference Design



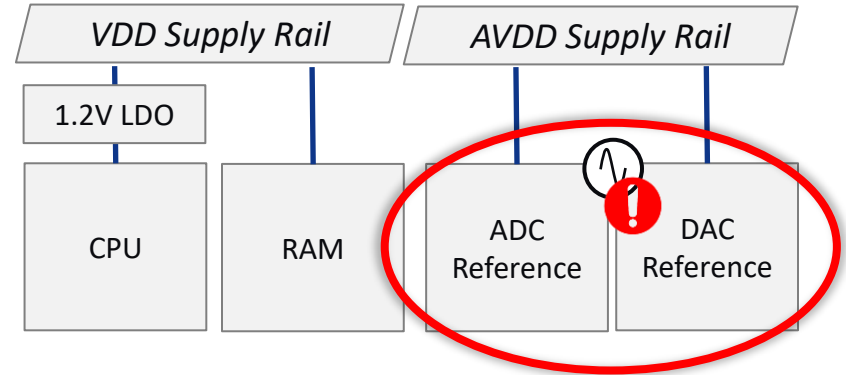
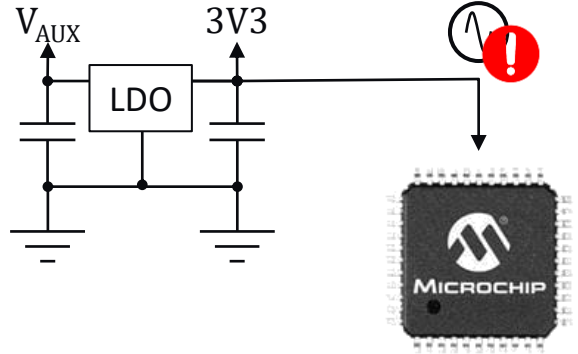
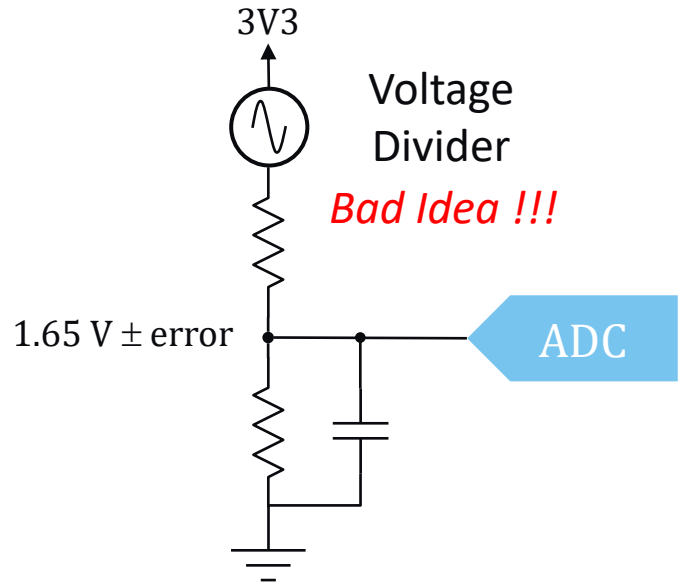
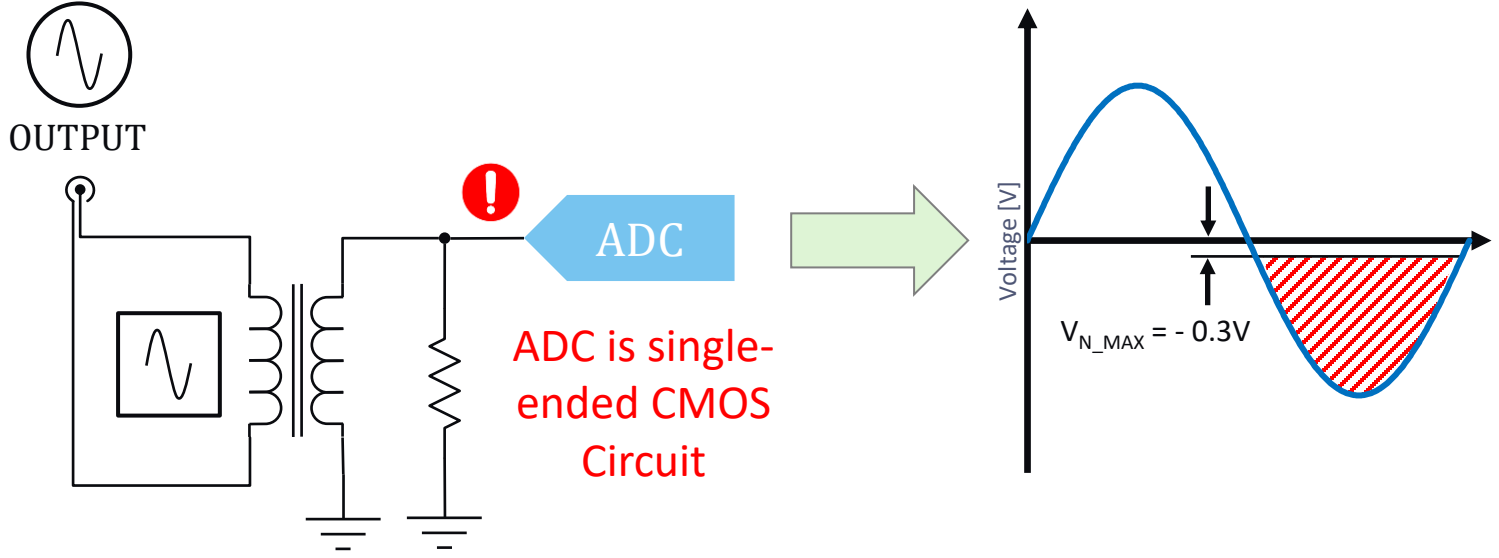
30 kW Vienna Rectifier
MCHP SiC Reference Design

Part-No. Single Core Device: [MA330048](#)
Part-No. Dual Core Device: [MA330049](#)

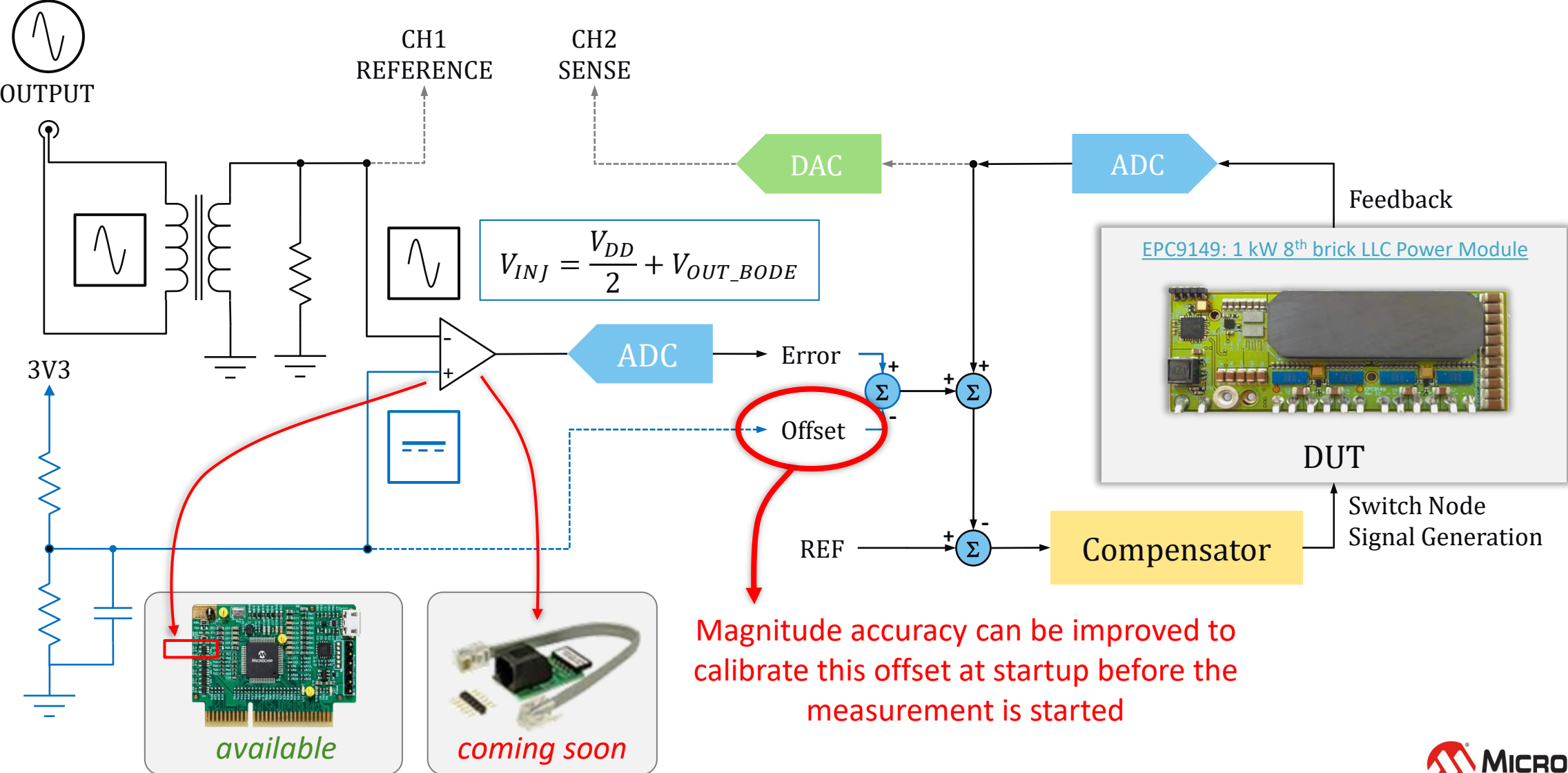
ADC Injection



ADC Injection

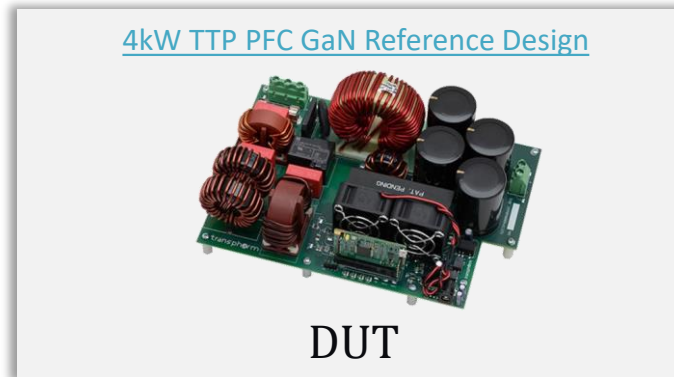
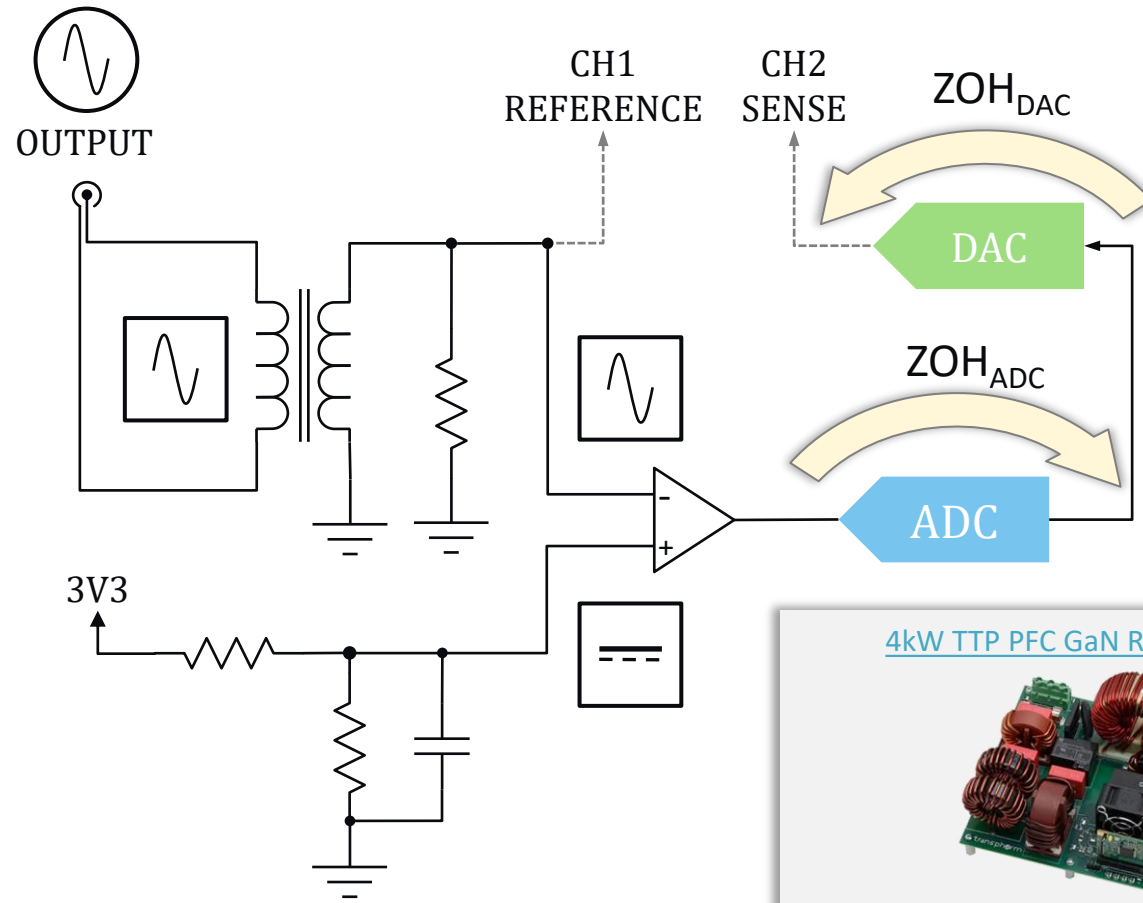


ADC Injection



Zero Gain Calibration

“Short-Cutting” ADC Input to DAC Output for ZOH Compensation Post Processing



- **Zero Order Hold (ZOH) delays** cause high frequency gain distortions, which requires compensation

- **List of Delays:**

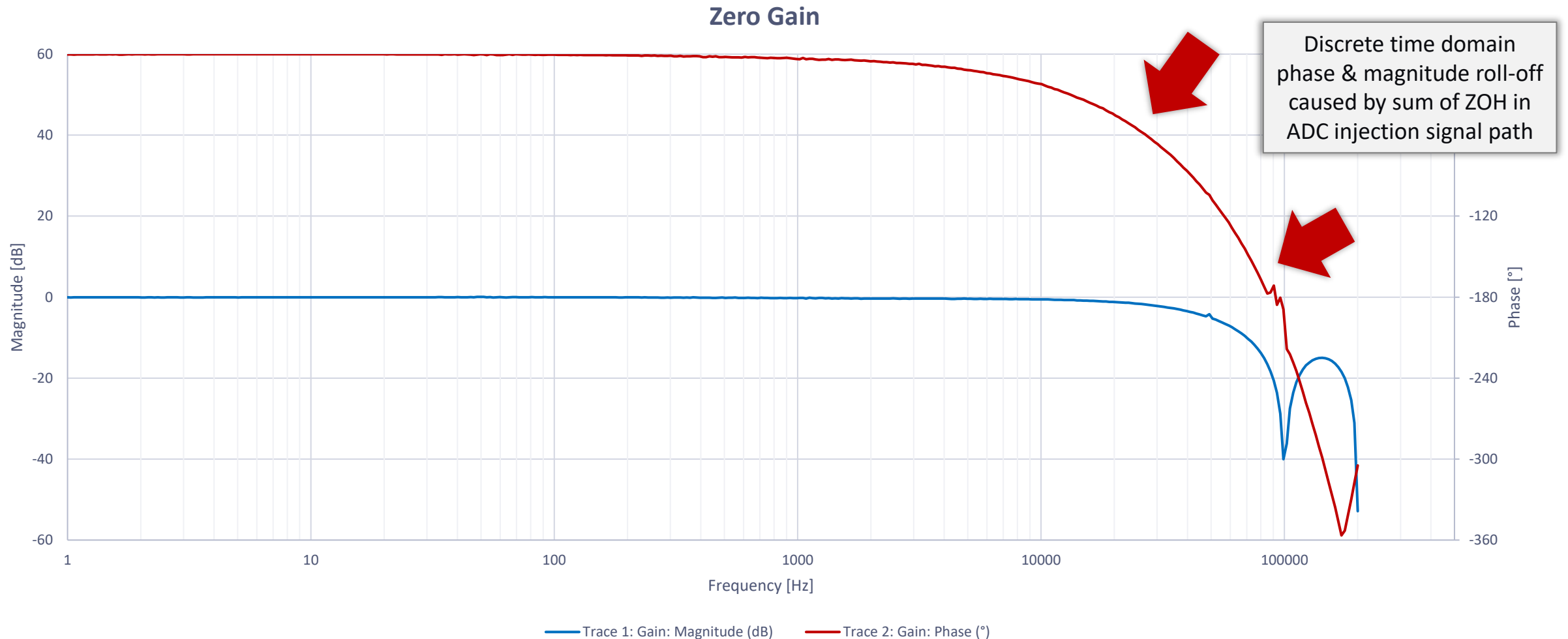
- ADC Trigger Frequency
- ADC Sampling & Conversion
- Interrupt Latency
- DAC Settings Time

- **Calibration Measurement**

- Measures the sum of all delays in the ADC injection signal path
- ADC sample of most recent injected error signal is routed directly back to DAC output without further processing

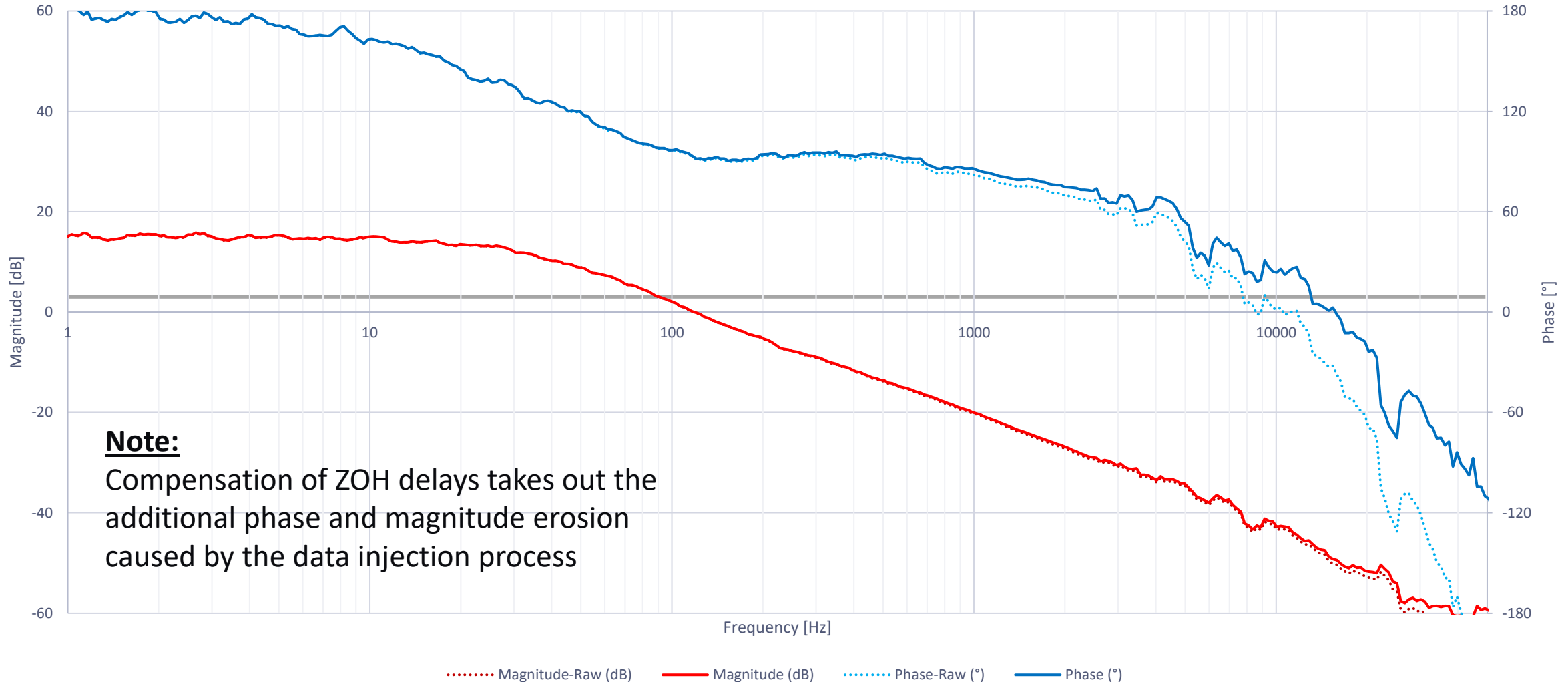
Zero Gain Calibration

“Short-Cutting” ADC Input to DAC Output for ZOH Compensation Post Processing



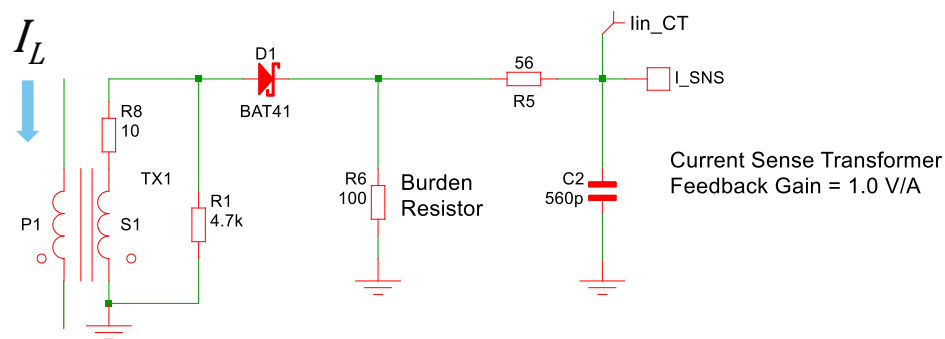
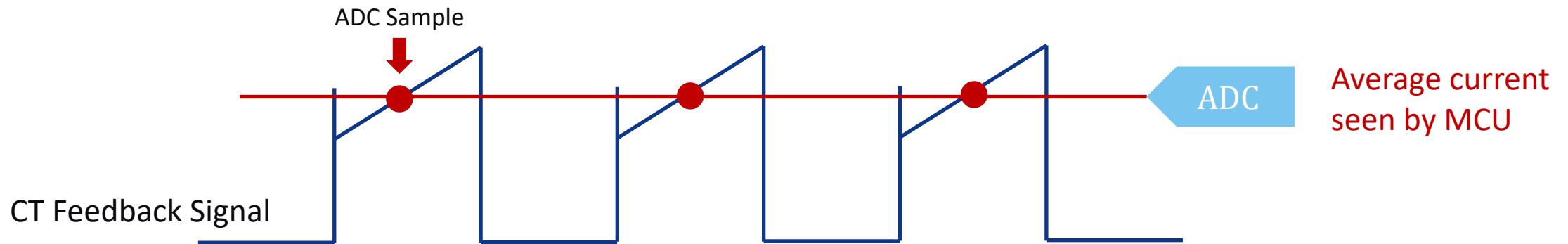
Measurement Results 2.5 kW TTP PFC

ZOH Compensated Open Loop Gain



Further Benefits of Decoupled Data Injection

- Only discrete samples of the injected signal is seen by the MCU
- Hence, discontinuous feedback signals do not have any influence on the measurement result (see Current Sense Transformer Example below)



Advantage:

Error signal is not injected in feedback path and thus does not create negative voltages during the signal off-time.

Agenda

- System Modelling Challenges
- Frequency Domain Design: The Basics
- Plant Frequency Response Measurements
 - Constant Gain Feedback Loop
 - Digitally Decoupled Injection (non-invasive)
- **Summary**

- Appendix:
 - In-Chip Measurement

Summary

- **Measuring the plant is complementary to simulation**
 - Measurements do not have the degree of visibility like simulations; Hence, measurements cannot be used as replacement but are vital for model validation
 - Measuring the plant transfer function offers additional insights
- **Digital Control allows**
 - Decoupled measurements for higher system and personal safety when working at high voltage designs
 - Measuring inaccessible circuits
 - Solves physical signal dependency issues
- **Further use-cases:**
 - Offline Control Loop Validation, filter development, dynamic code tests...

Thank You!

May the Power be with you

Appendix

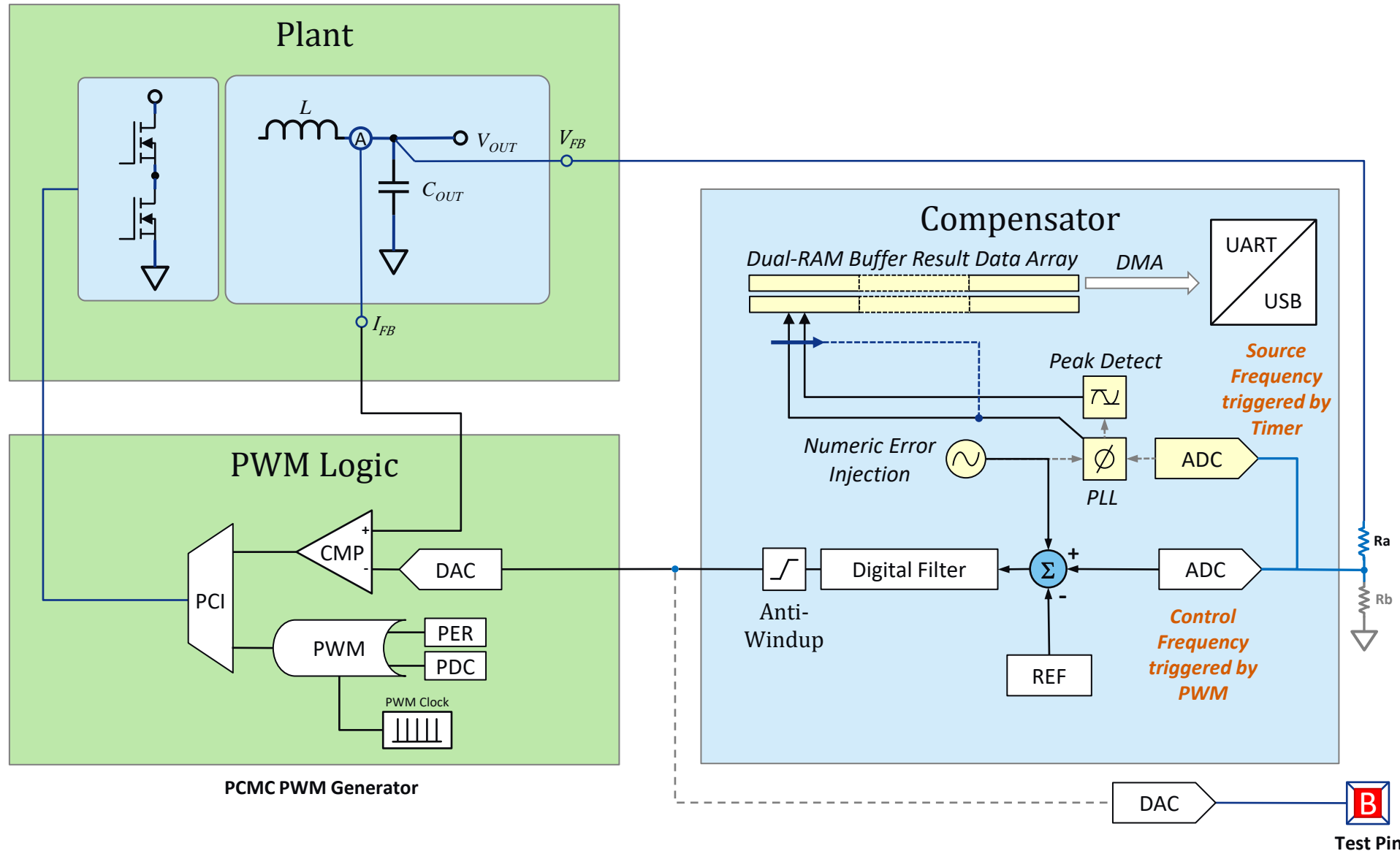
Additional Information

Agenda

- System Modelling Challenges
- Frequency Domain Design: The Basics
- Plant Frequency Response Measurements
 - Constant Gain Feedback Loop
 - Digitally Decoupled Injection (non-invasive)
- Summary

- **Appendix:**
 - In-Chip Bode Measurement

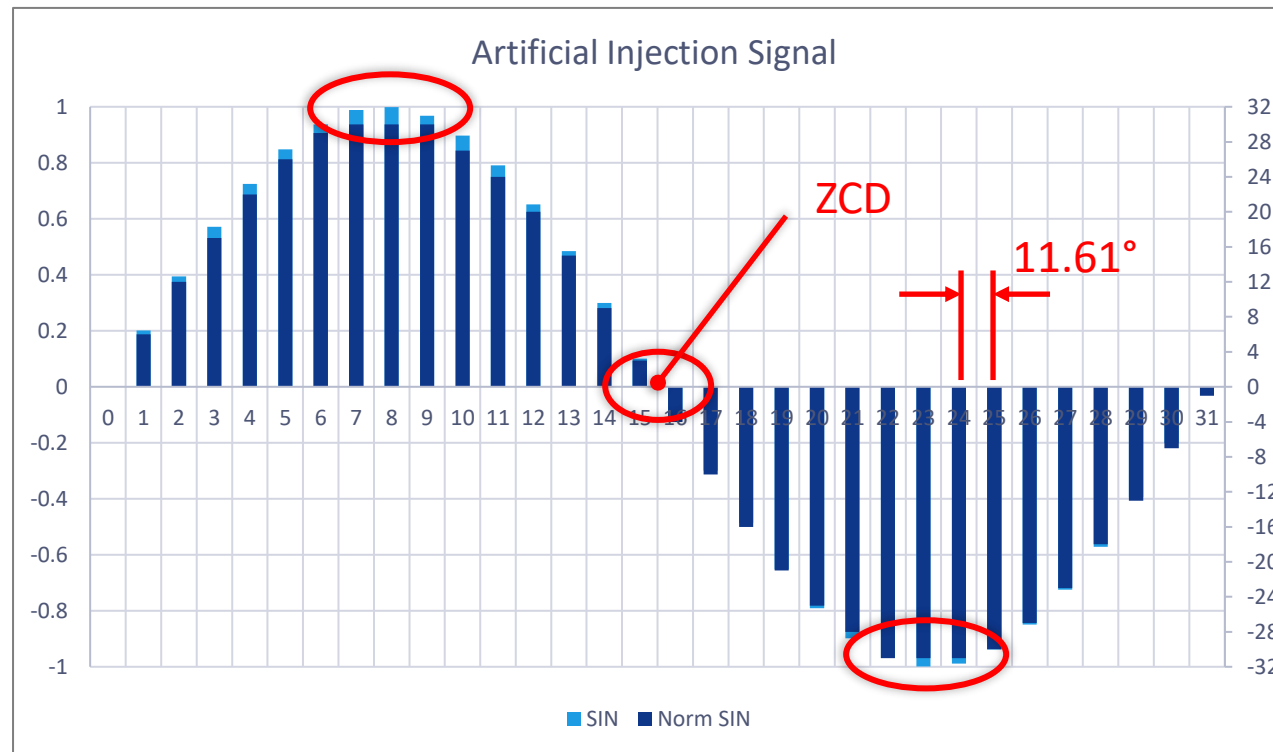
In-Chip Bode Measurement



Digital PWM Controller Access Points

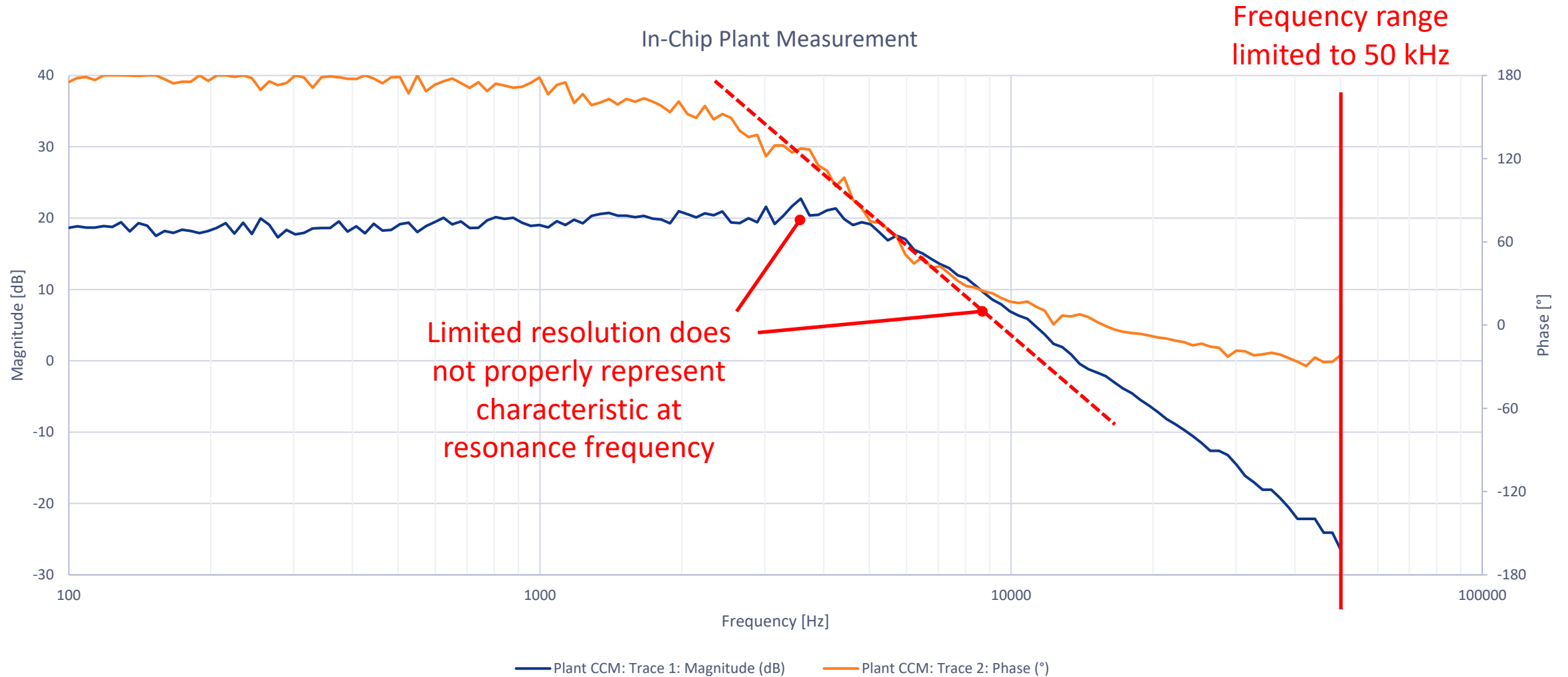
- **Numeric Injection:**

- Nominal feedback signal level is considered as constant offset (here 2048 ADC ticks = 1.65 V feedback voltage)
- Artificial signal injection uses signed 6-bit wide fractional numbers normalized to = 1, embedded as lookup table
- Injecting sinusoidal frequency in loop is performed with $[frequency] \times [series\ size] = 50\ kHz \times 32 = 1.6\ MHz$



Typical Results

500 kHz Buck Converter Voltage Mode Example



Digital PWM Controller Access Points

Pros

- Does not require ***additional*** device pins
 - Programming/Debugging interface is reused*
 - Data post processing on PC / integrates in existing firmware

Cons

- **Limited Resolution**
 - Phase angle depends on sampling speed
 - Magnitude resolution limited by 12-bit ADC
 - Sample delay influences phase accuracy
- **Data Capture**
 - Only works under bench conditions
 - Available amount of data is limited by internal RAM
 - High, additional CPU load sometimes hard to integrate with full software implementation / risk of interference with real time control leading to even worse data accuracy
- **Data exchange:**
 - If UART is used, interface IC circuit is required
 - If debugger is used, device must be halted to read data

Conclusion:

Maybe useful for corner cases but overall, too limited to be practical

Appendix

Introduction of Digital Power Starter Kit 3
featuring dsPIC33CK Switch-Mode Power DSC

Digital Power

- **Getting Started in Digital Power**

- Intelligent Power Design Center:

<https://www.microchip.com/power>

- **How-2 Starter Kits**

- Digital Power Starter Kit 3 (Part-No. DM330017-3):

<https://www.microchip.com/dm330017-3>

- **Training:**

- Microchip University (Virtual Training Platform):

<https://secure.microchip.com/mu>

Please note:

All Face-2-Face workshops have been suspended in early 2020, including the well-known MASTERS conferences usually conducted in 9 nations around the globe. For the time being all available trainings have been moved to our new virtual training platform ***Microchip University***.

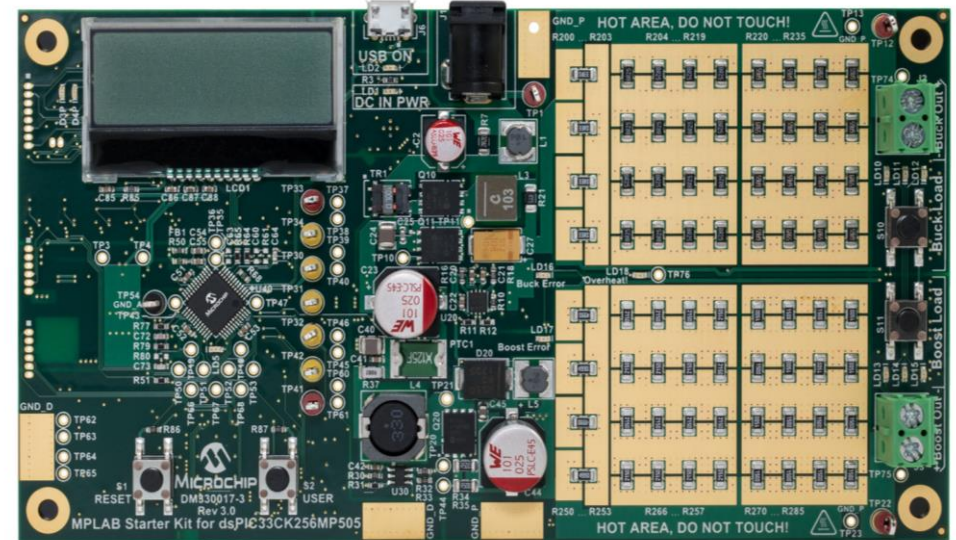


dsPIC33C Digital Power Starter Kit

New

Features:

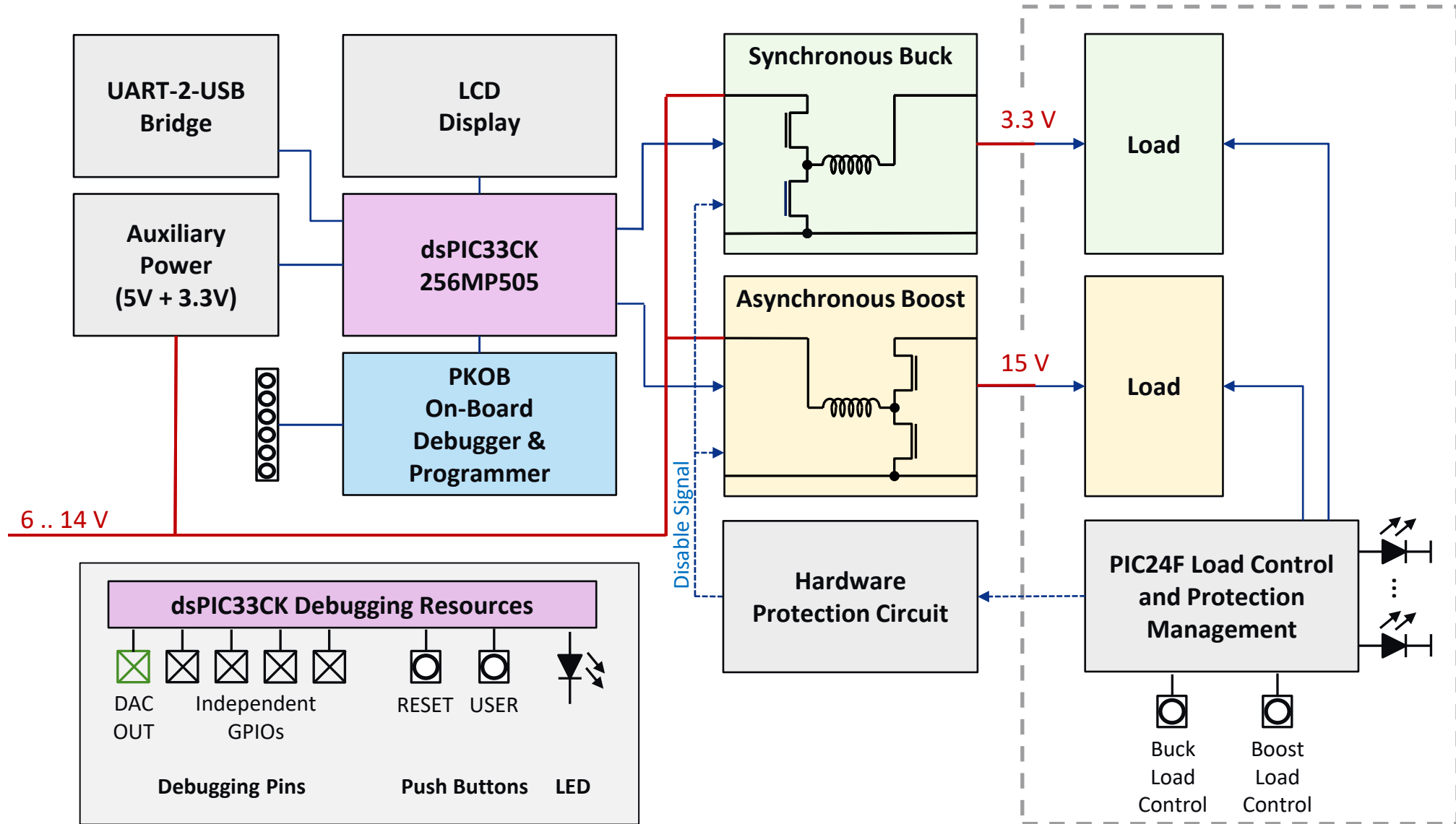
- On-board **dsPIC33CK256MP505** DSC
- Independent DC/DC synchronous Buck and Boost converters
- Independent resistive loads
- Protection circuitry
- LCD display user interface
- USB/UART converter/bridge
- On-board programmer/debugger circuitry
- Both power stages are controlled by the dsPIC33CK DSC
- Loads and protection circuitry are controlled by a PIC24 auxiliary microcontroller



Available Now:

Order # DM330017-3

Digital Power Starter Kit 3 (DPSK3)



dsPIC33C Digital Power Starter Kit

List of Microchip Components used

Microchip Technology Focus Devices

- [48-pin Digital Signal Controller, dsPIC33CK256MP505](#)

Further Microchip Technology Devices used

a) Power Supply Circuit

- [8-MHz MEMS Oscillator, DSC6011JI2A-008](#)
- [50V/1A, Asynchronous Buck Regulator, MCP16331](#)
- [16V/300mA Low Quiescent Current LDO with Shutdown and Power Good, 3.3V, MCP1755-330](#)
- [High-Speed Low-Side MOSFET Driver, MCP14A0152](#)
- [Dual Input Synchronous Half-Bridge MOSFET Driver, MCP14700](#)
- [High-Speed N-Channel MOSFET, MCP87130](#)
- [Active Thermistor Temperature Sensor, MCP9700](#)

b) Protection Circuit

- [P-Channel Enhancement-Mode MOSFET, TP2104](#)
- [36V Open-Collector Comparator, MIC6270YM5](#)
- [Windowed Comparator with Adjustable Hysteresis, MIC841H](#)
- [50V/5A Schottky-Diode, HSM560JE3](#)

c) Communication and Housekeeping

- [2-Port USB 2.0 HUB Controller, USB2422](#)
- [USB 2.0 to I2C/UART Protocol Converter, MCP2221A](#)
- [44-pin MCU PIC24FJ64GA004](#)

d) Programming/Debugging

- [ARM® Cortex®-M7 ATSAME70N21B-ANT](#)
- [12 MHz MEMS Oscillator DSC6011JI2A-012](#)
- [256Kb I2C Serial EEPROM 24LC256](#)
- [1.5A Low Voltage LDO, MCP1727](#)
- [1.8V Low-Power Open-Drain Output Comparator, MCP6566](#)

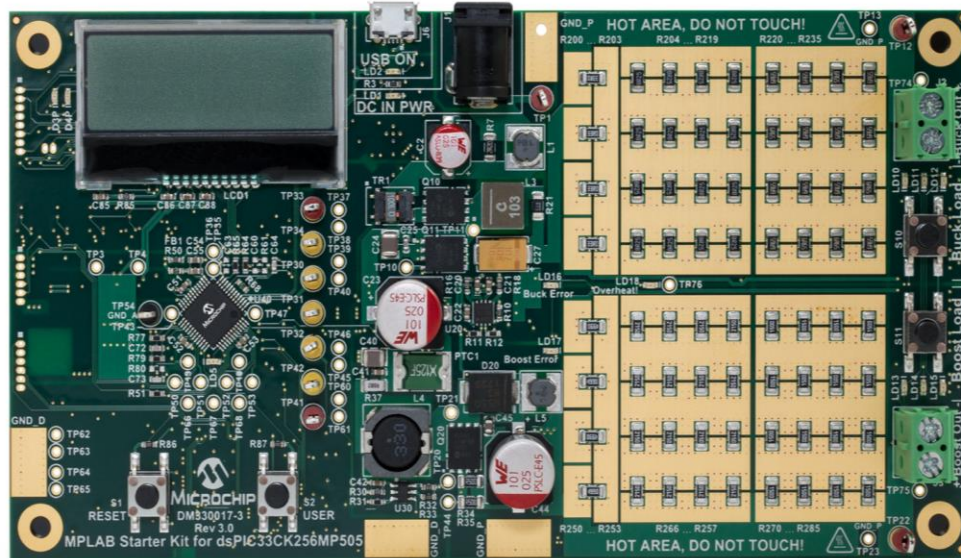
dsPIC33C Digital Power Starter Kit

New

Visit:

<https://www.microchip.com/DM330017-3>

for more information



Available Now:


Order # DM330017-3

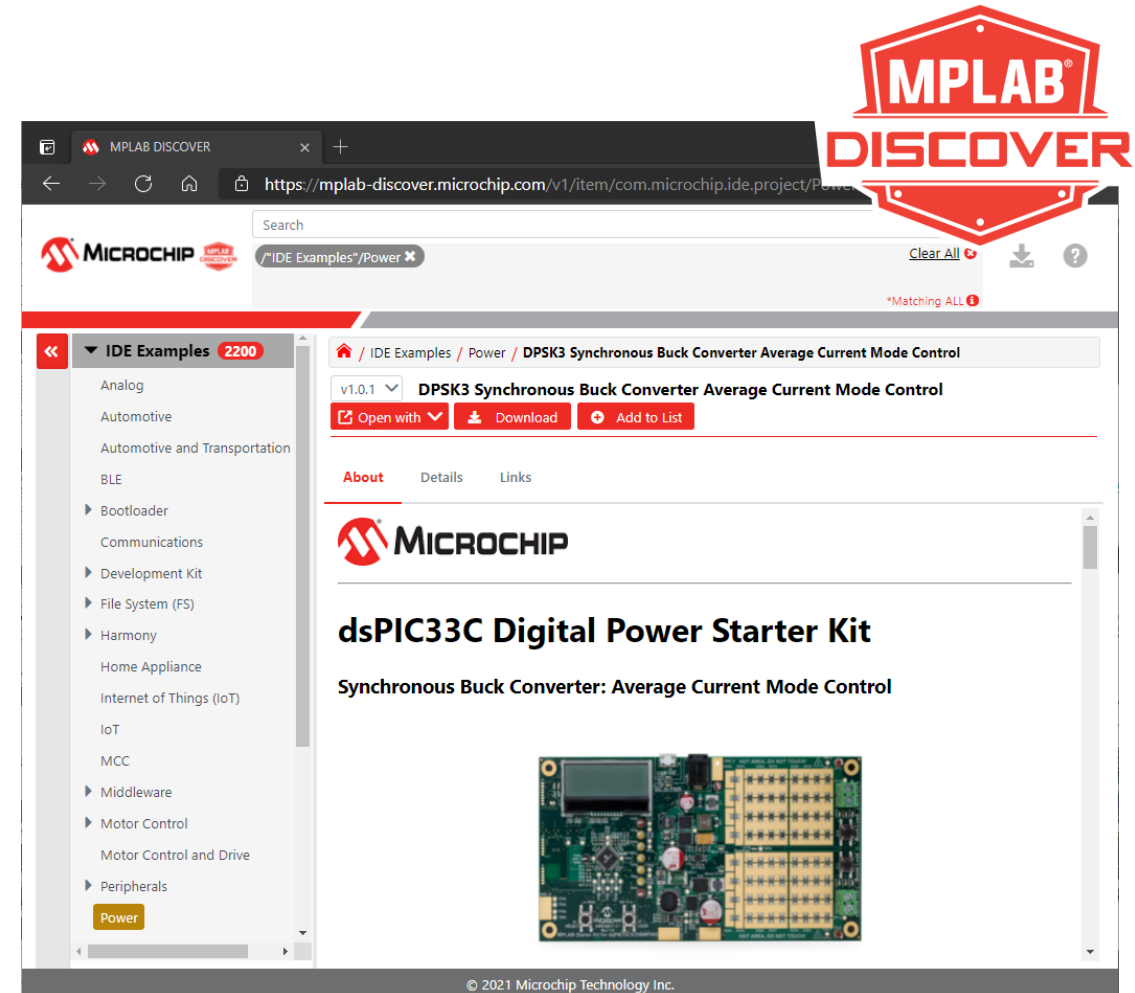
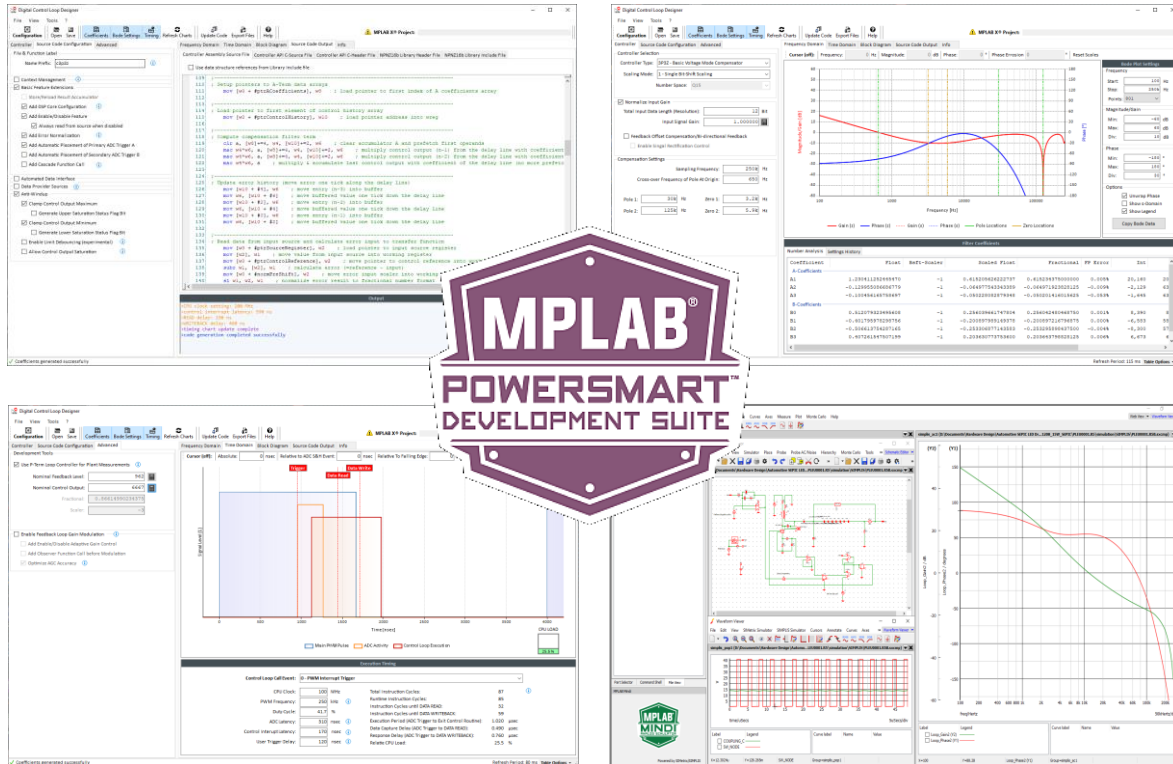
Available Code Examples

- **Out-Of-The Box Firmware** Released
 - Operating all blocks simultaneously
- **Buck Converter**
 - Voltage Mode Control (VMC) Released
 - Adaptive Voltage Mode Control (AVMC) Released
 - Peak Current Mode Control (PCMC) Released
 - Average Current Mode Control (ACMC) Released
- **Boost Converter**
 - Voltage Mode Control (VMC) Released
 - Adaptive Voltage Mode Control (AVMC) Pending
 - Peak Current Mode Control (PCMC) Pending
 - Average Current Mode Control (ACMC) Pending
 - Predictive Input/Output Linearization (PIOL) Pending

Digital Power Design Resources



- Find all code examples and design tools in one place: <https://discover.microchip.com>
- Code examples available as ZIP Archives and open repositories on Github  <https://github.com/microchip-pic-avr-examples>



Thank You!

May the Power be with you