Practical System Modelling using Bench Measurements of Plant Transfer Functions

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Power Conversion

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

MICROCHIP

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Why Measuring the Plant Gain Matters

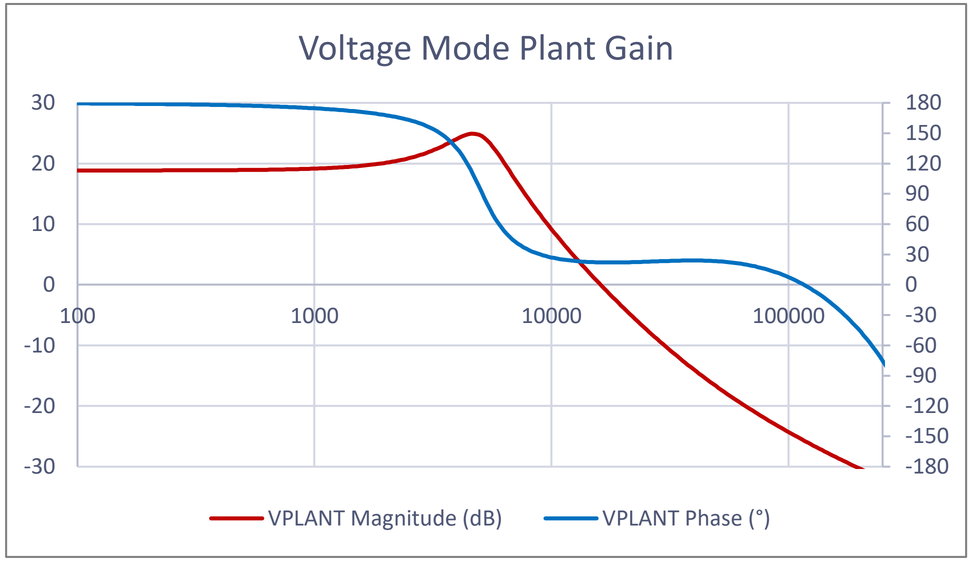
- **The plant transfer function is the essential system component of every power supply design**

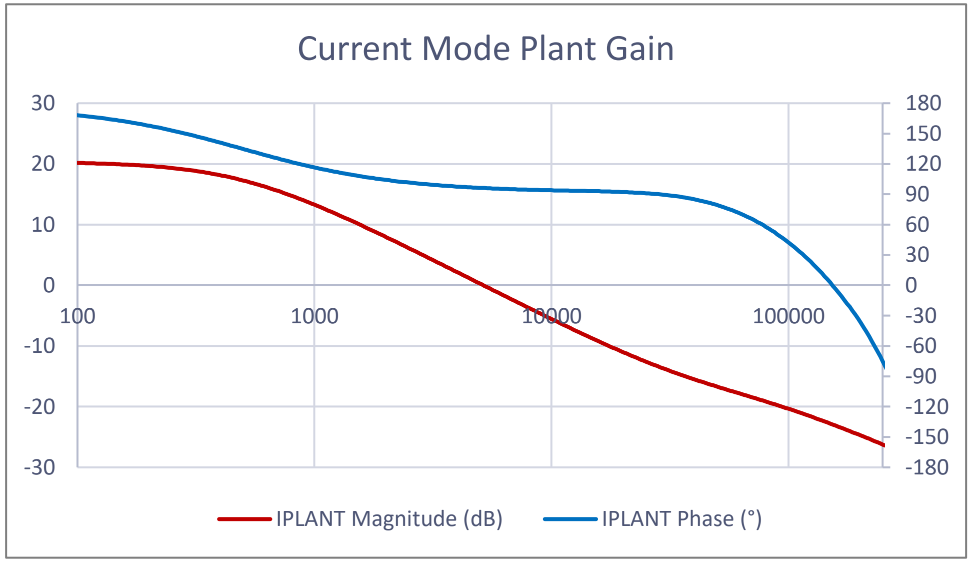
- **The plant frequency response is influenced by the following factors:**

  - 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!**

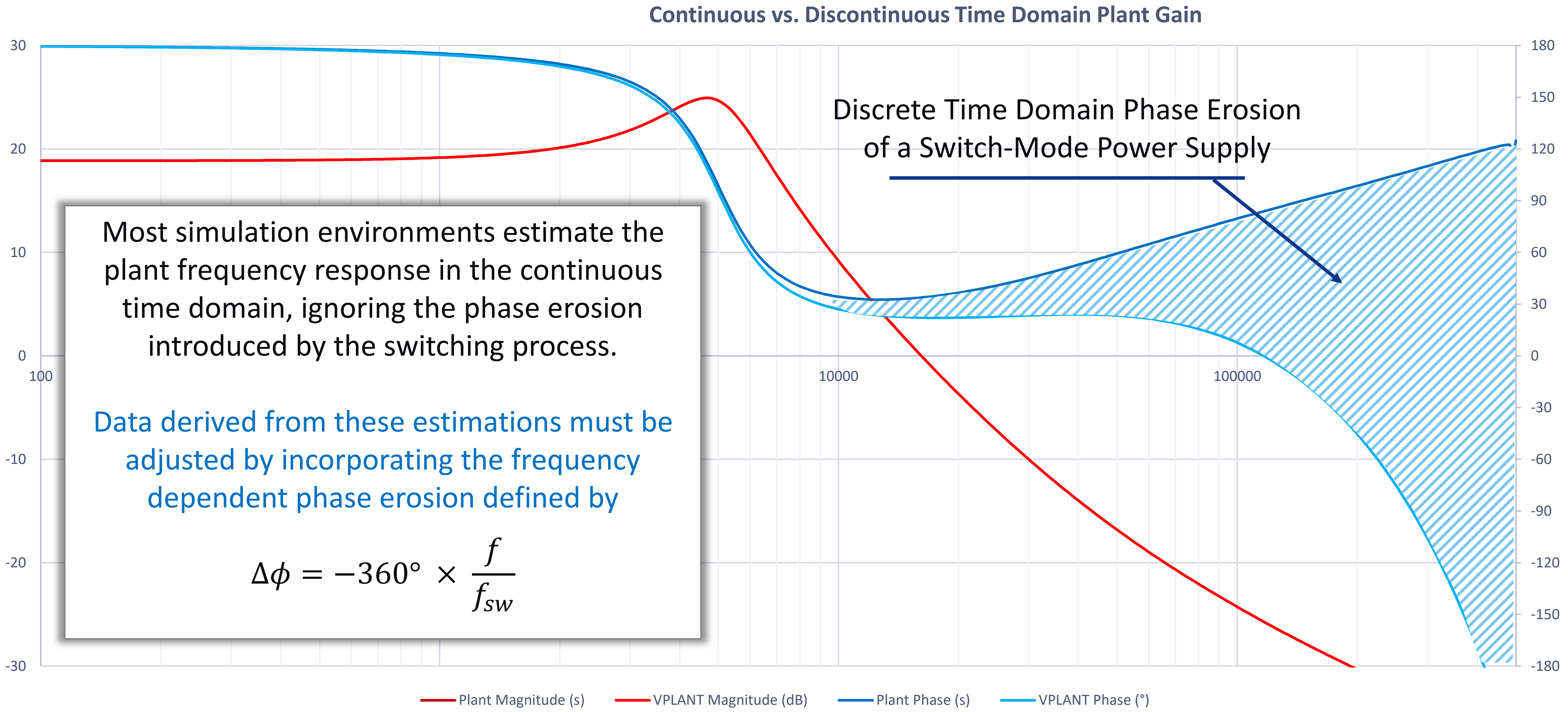




Common Design Steps

- **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



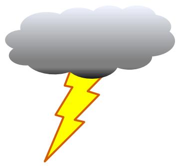
Most simulation environments estimate the plant frequency response in the continuous time domain, ignoring the phase erosion introduced by the switching process.

Data derived from these estimations must be adjusted by incorporating the frequency dependent phase erosion defined by

$$\Delta\phi = -360° \times \frac{f}{f_{sw}}$$

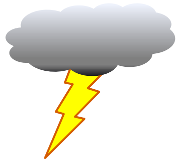
System Modeling Challenges

- **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)



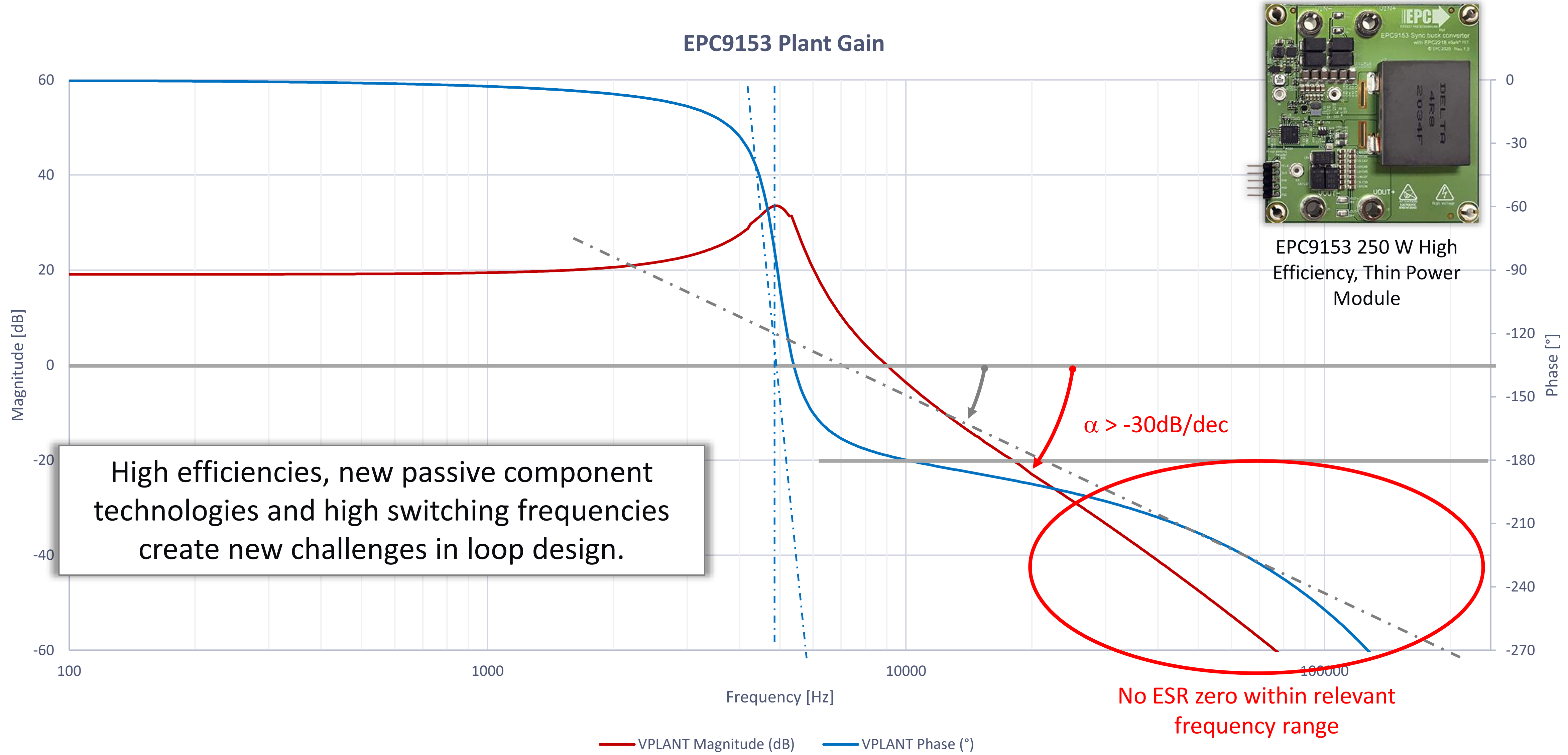
- *Not applicable in digital designs*
- *Not feasible for power supplies with efficiencies > 92% !*

  - Voltage Mode Controlled Power Supplies are always stable
    - Assumption:
      - Dominant ESR zero lies within switching frequency rage
      - Phase remains >-180°
        (Does not consider switching process phase erosion)



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

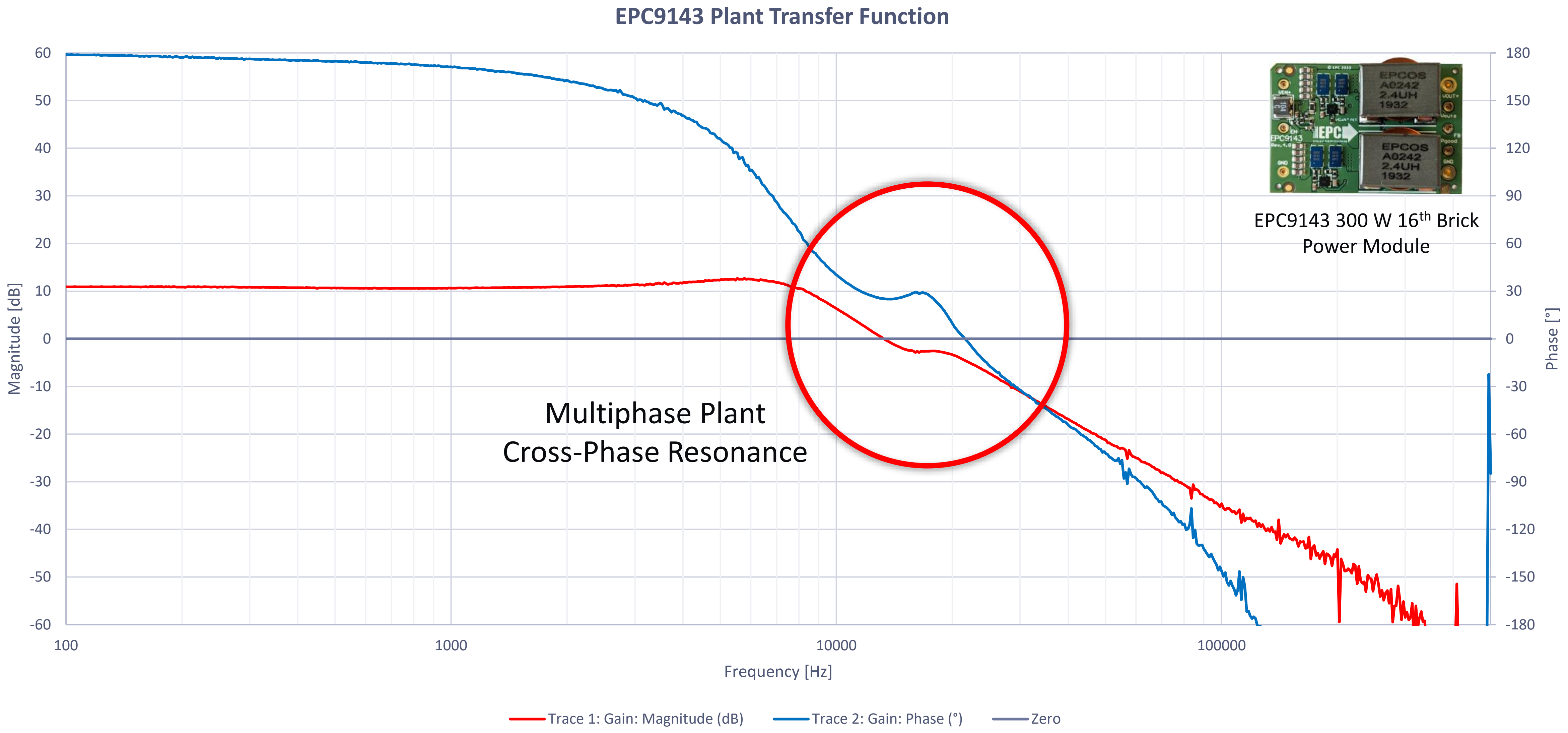
Plant Transfer Function of 98% Efficient Buck Converter



EPC9153 250 W High Efficiency, Thin Power Module

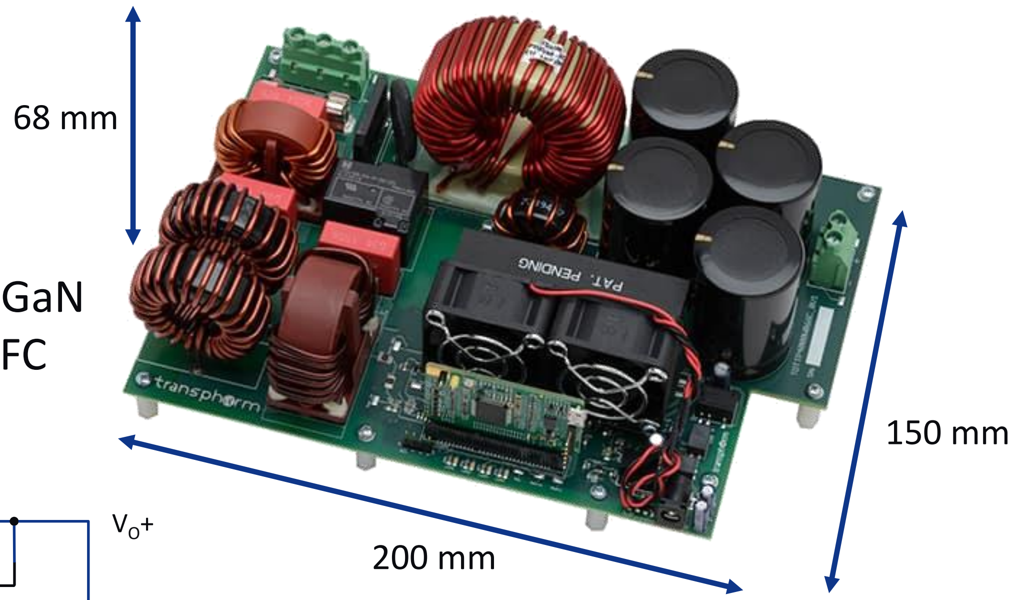
High efficiencies, new passive component technologies and high switching frequencies create new challenges in loop design.

Capturing Circuit Artefacts

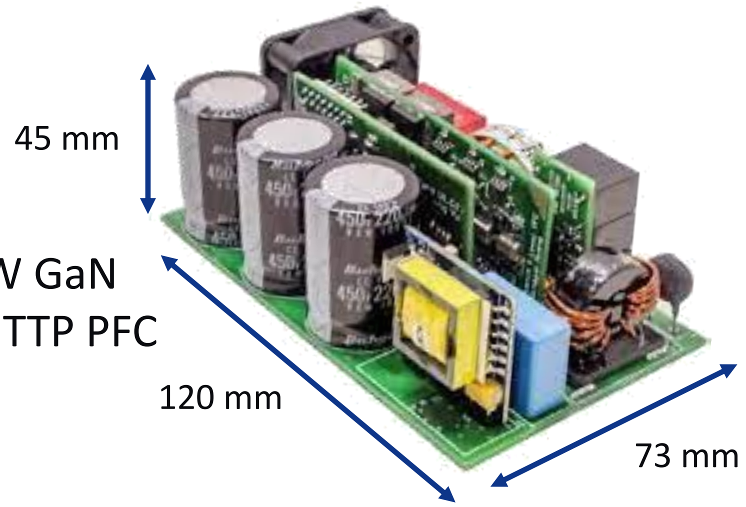


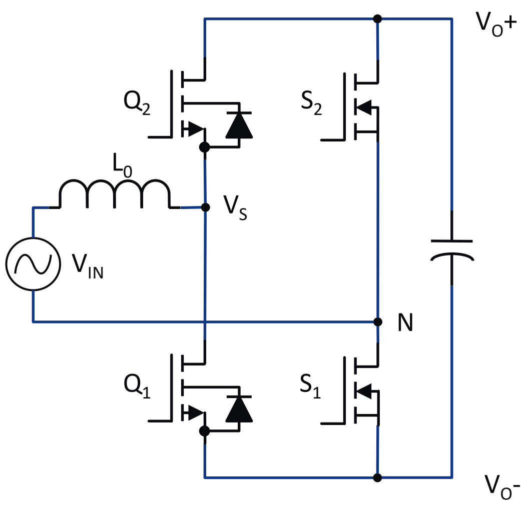
Continuous Topology Evolution

2.5 kW GaN
TTP PFC

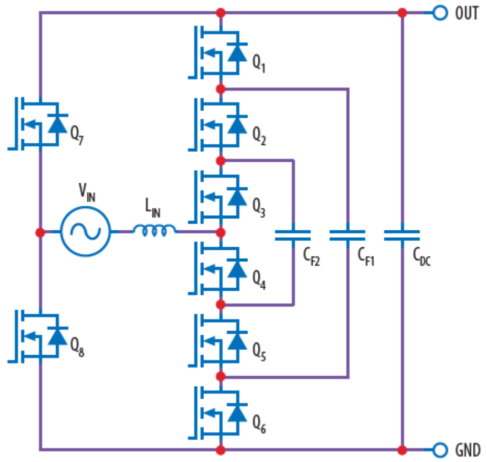


3 kW GaN
FCML TTP PFC





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



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

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

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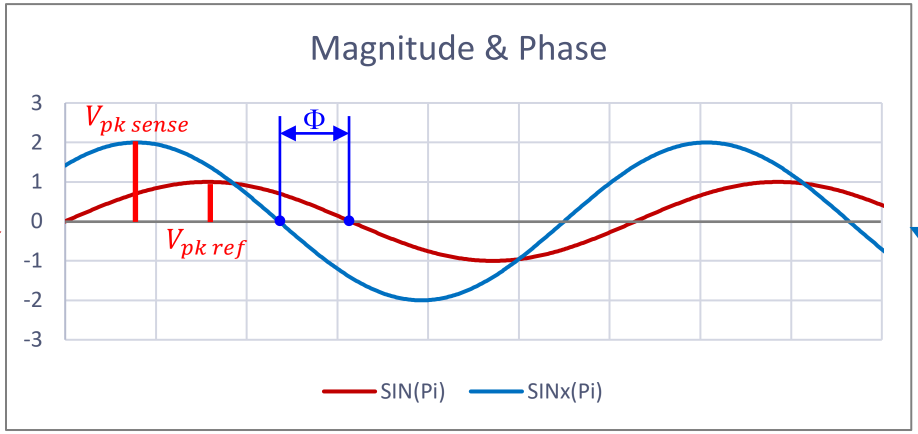
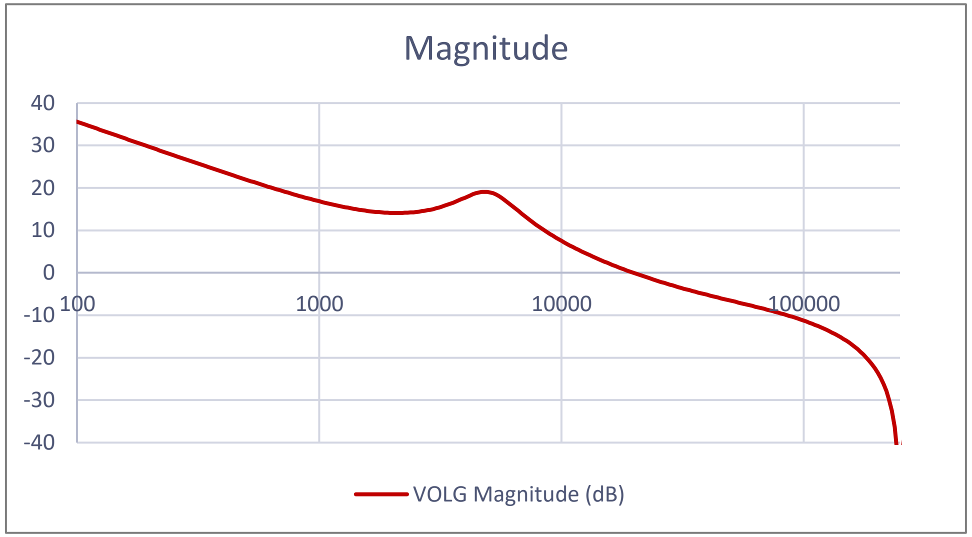
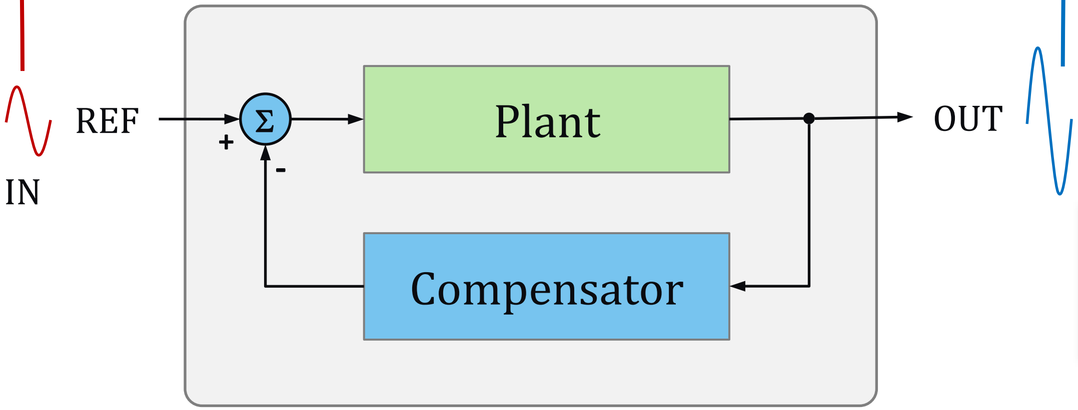
The Basics

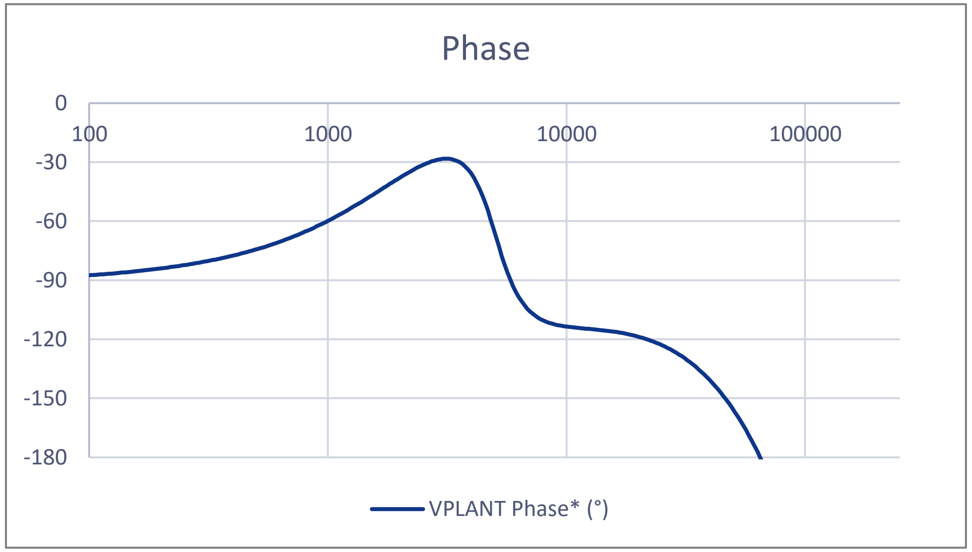


$$Mag = \frac{V_{pk\ sense}}{V_{pk\ ref}}$$





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

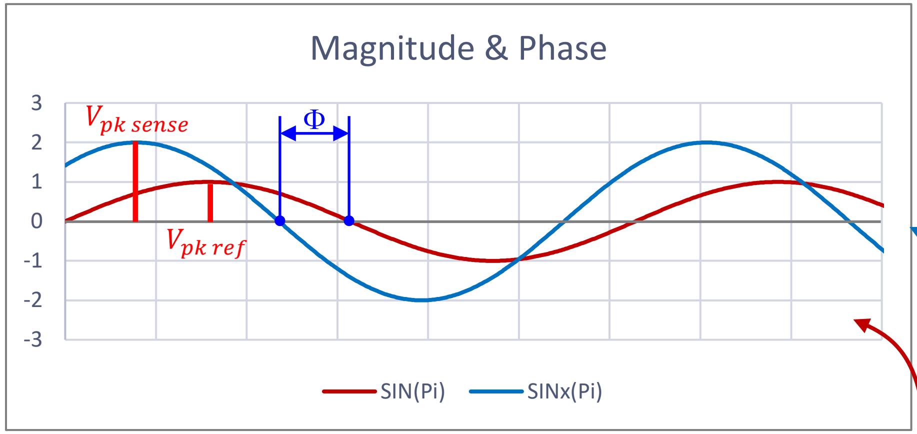


$$G_{CL}(s) = \frac{G(s)}{1 + G(s)H(s)}$$

Aspect of Analysis

Open Loop Gain in the Closed Loop System

The Basics



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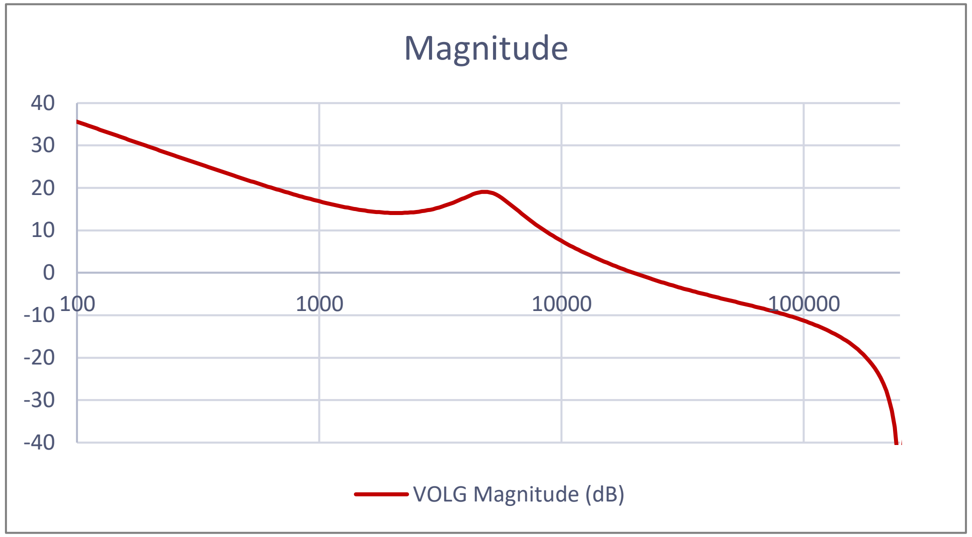

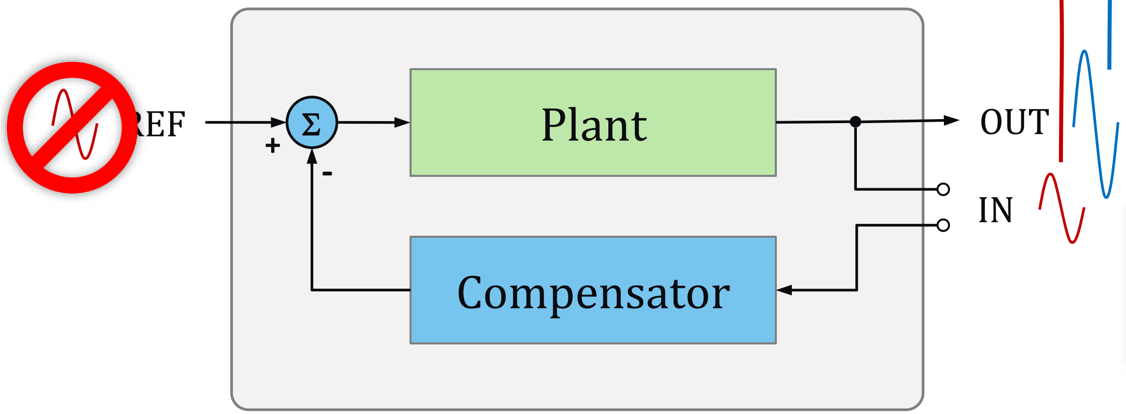

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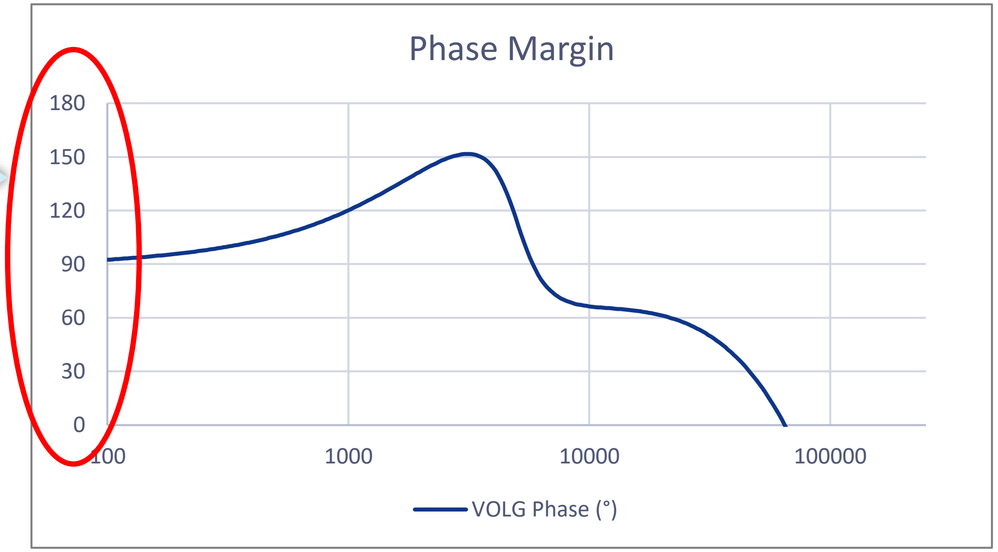

$$G_{CL}(s) = \frac{G(s)}{1 + G(s)H(s)}$$

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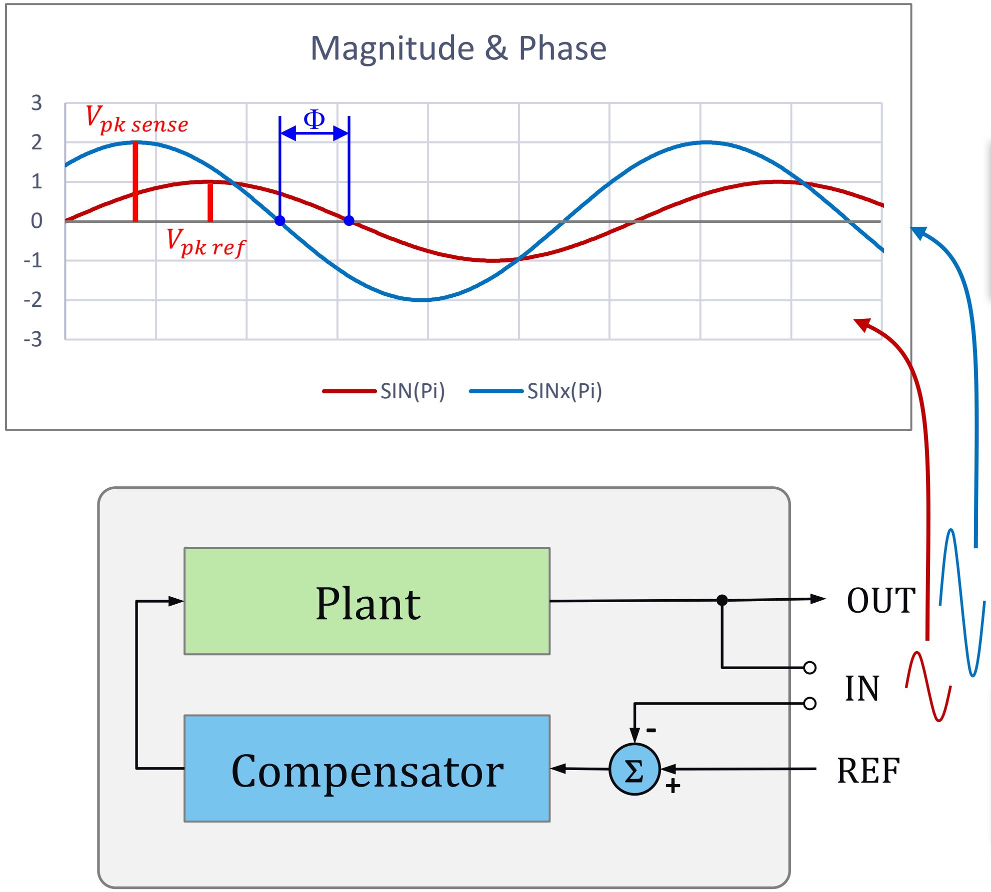
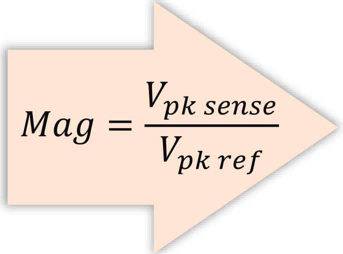
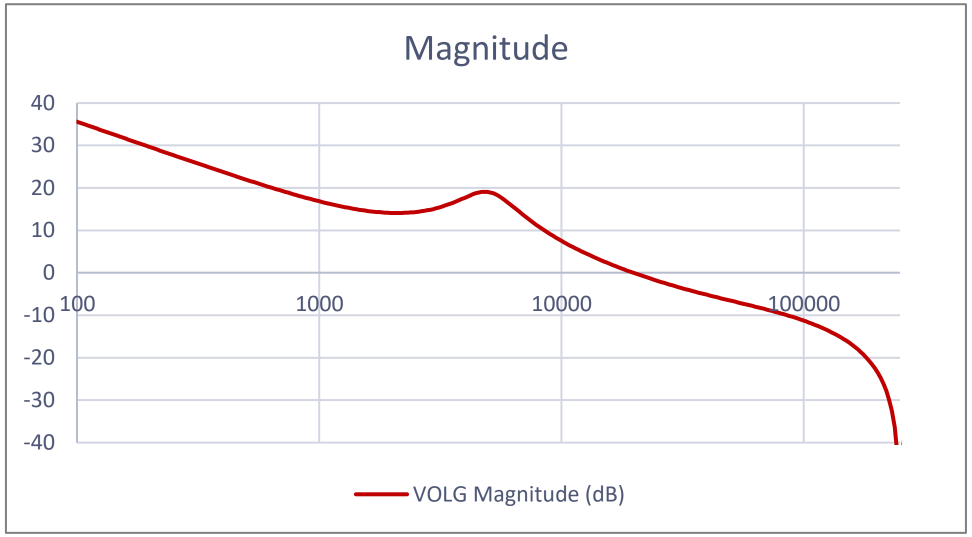
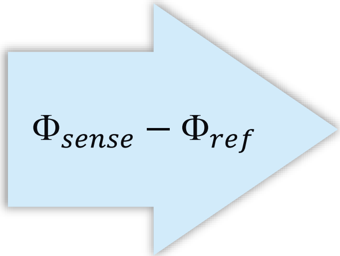
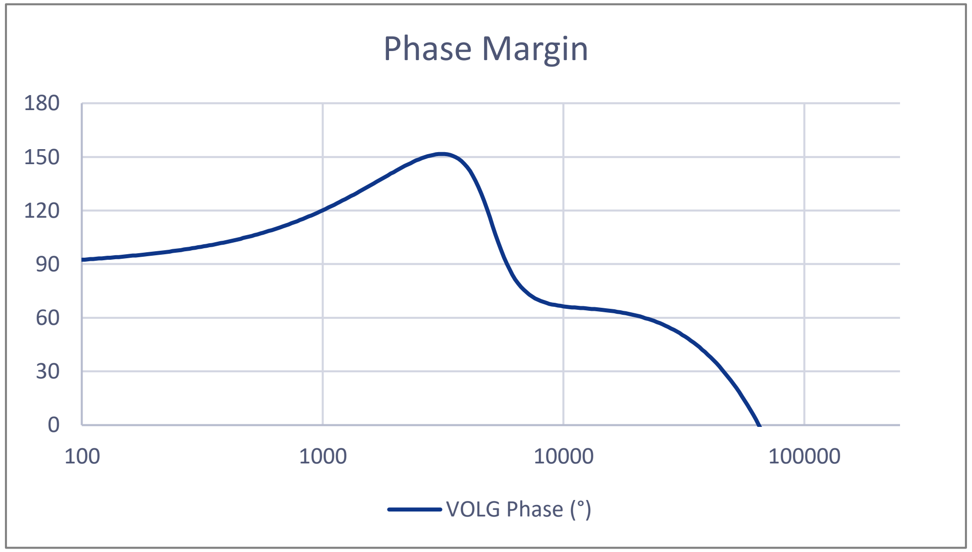
The Basics











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

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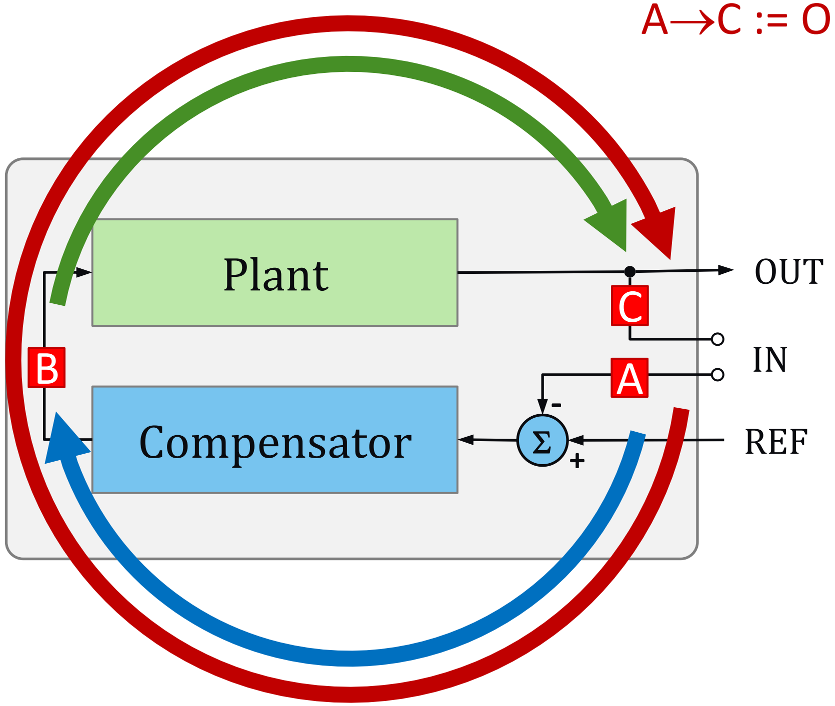
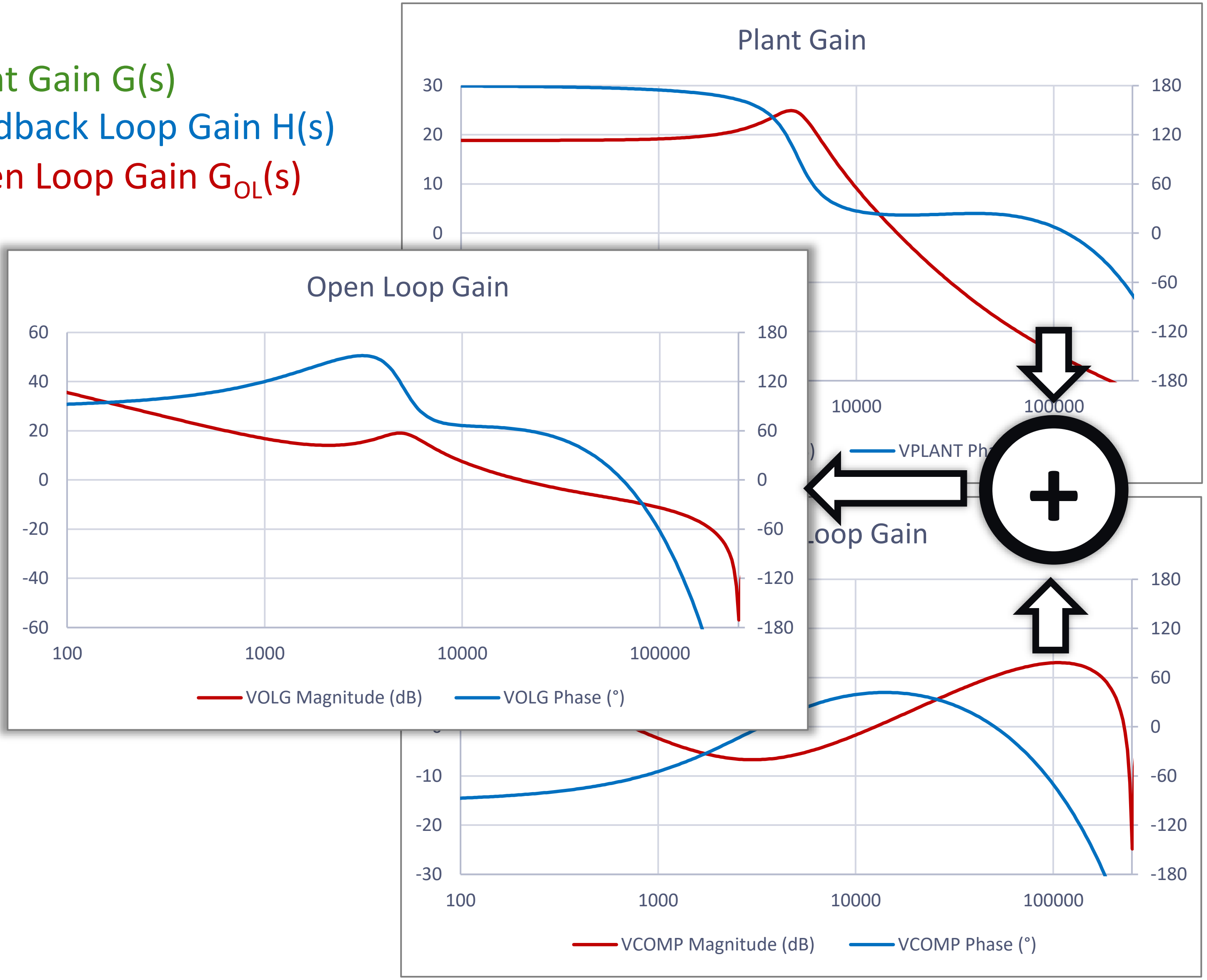
The Basics

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

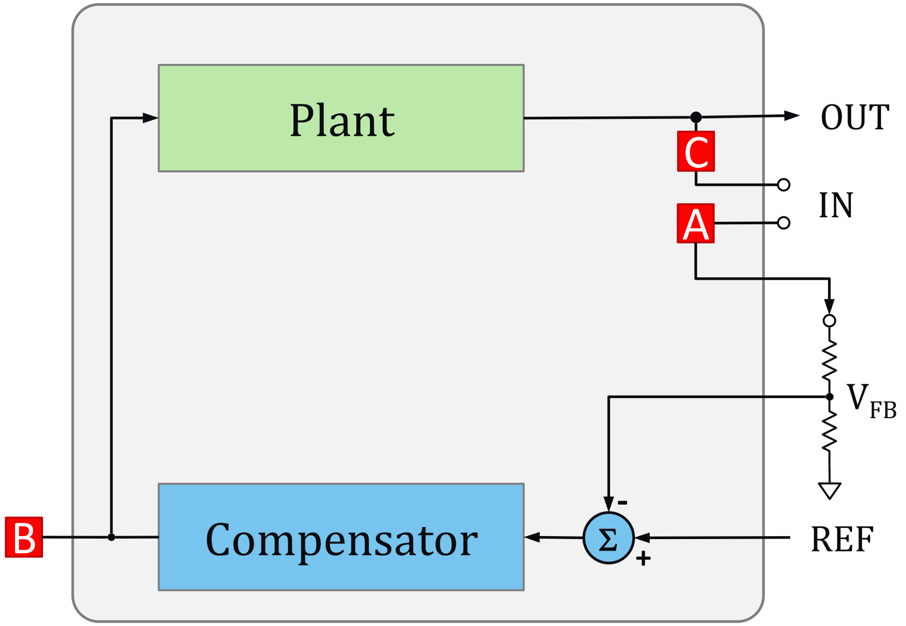




$$G_{OL}(s) = G(s) \times H(s)$$

Warning!

Signal



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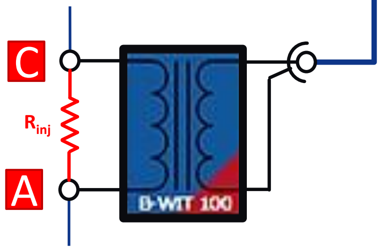
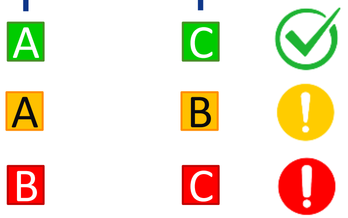
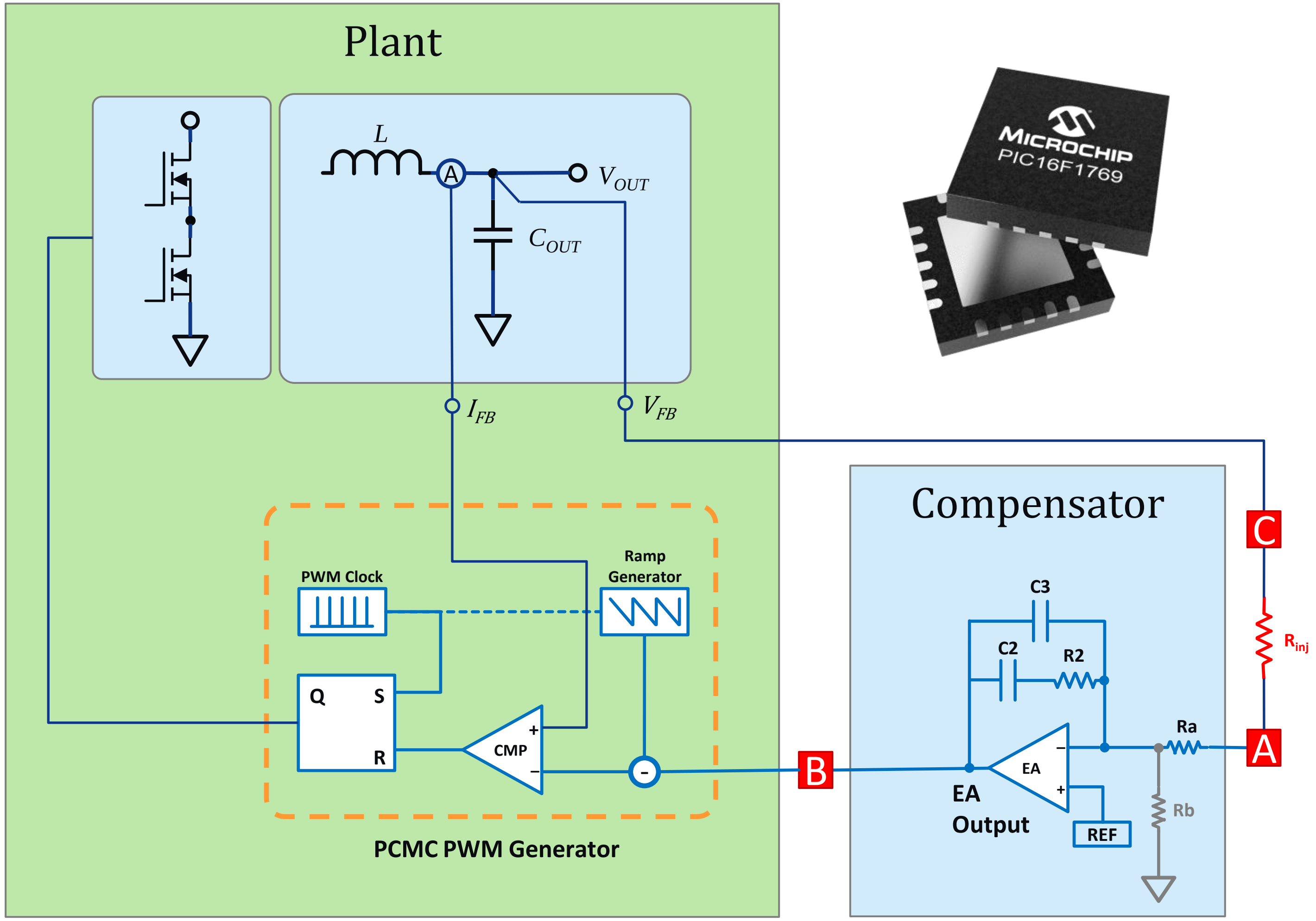
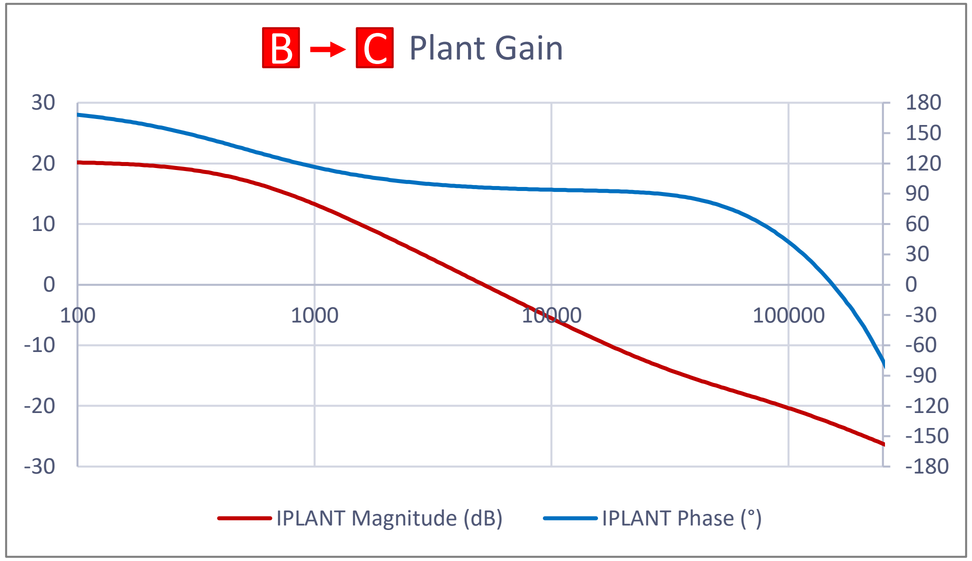


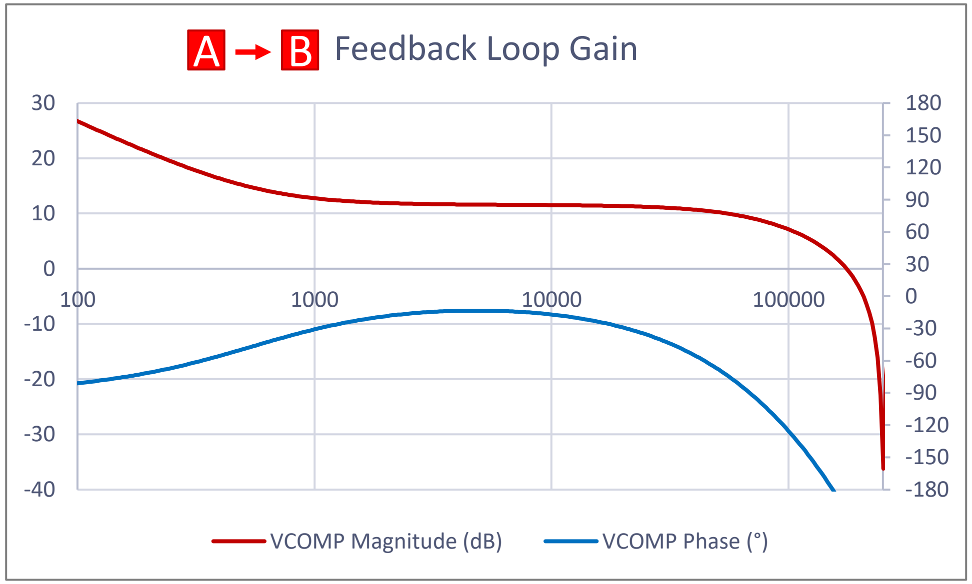
$\Delta V_{CH1\text{-}CH2\ MAX} \approx 4\ V$



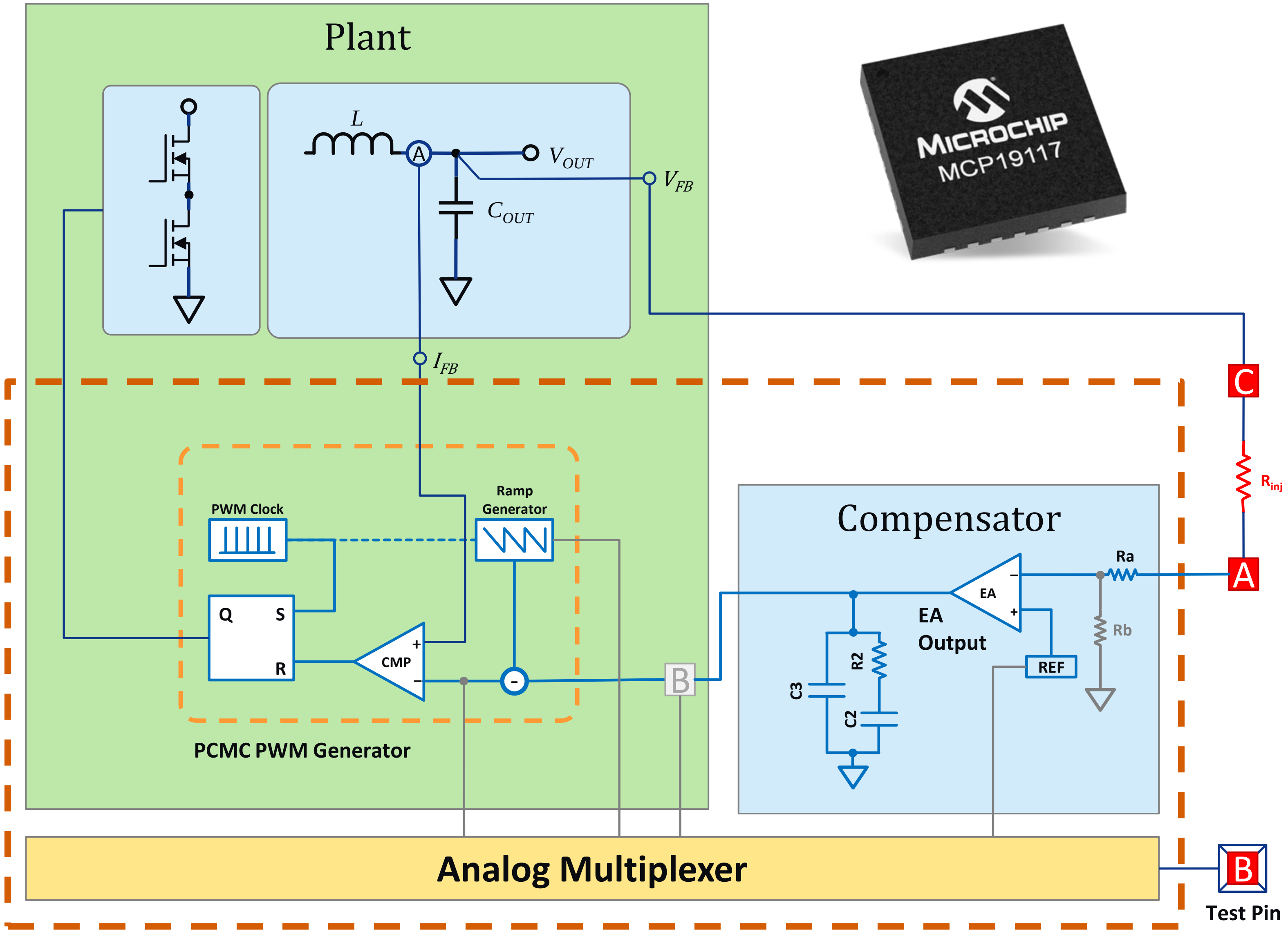
Analog PWM Controller Access Points

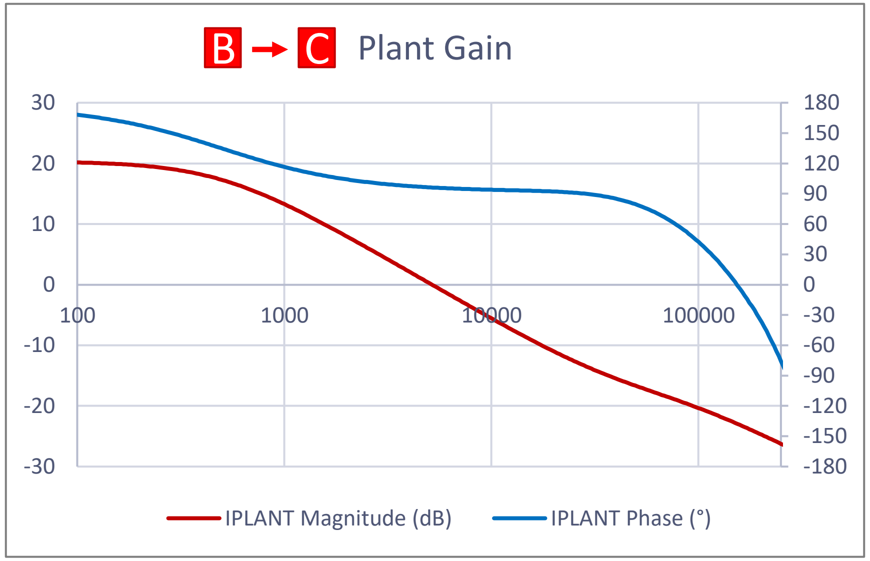


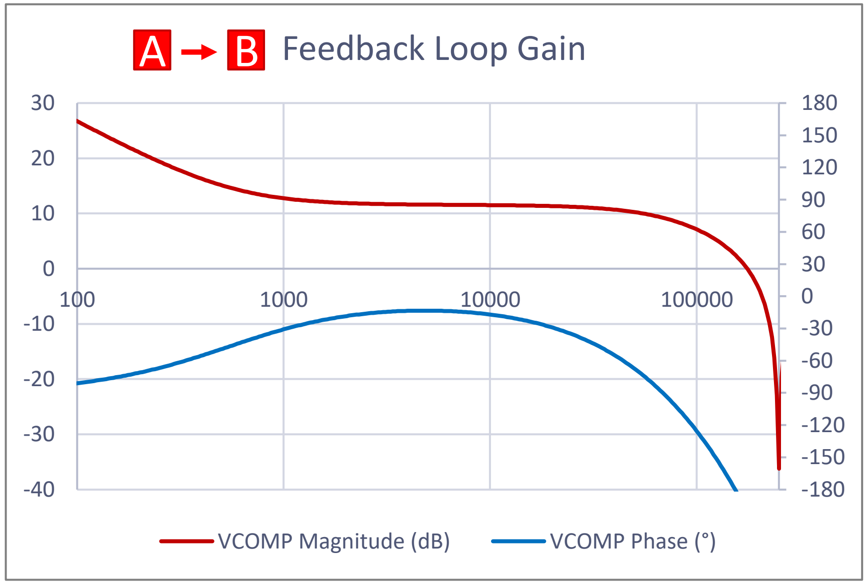




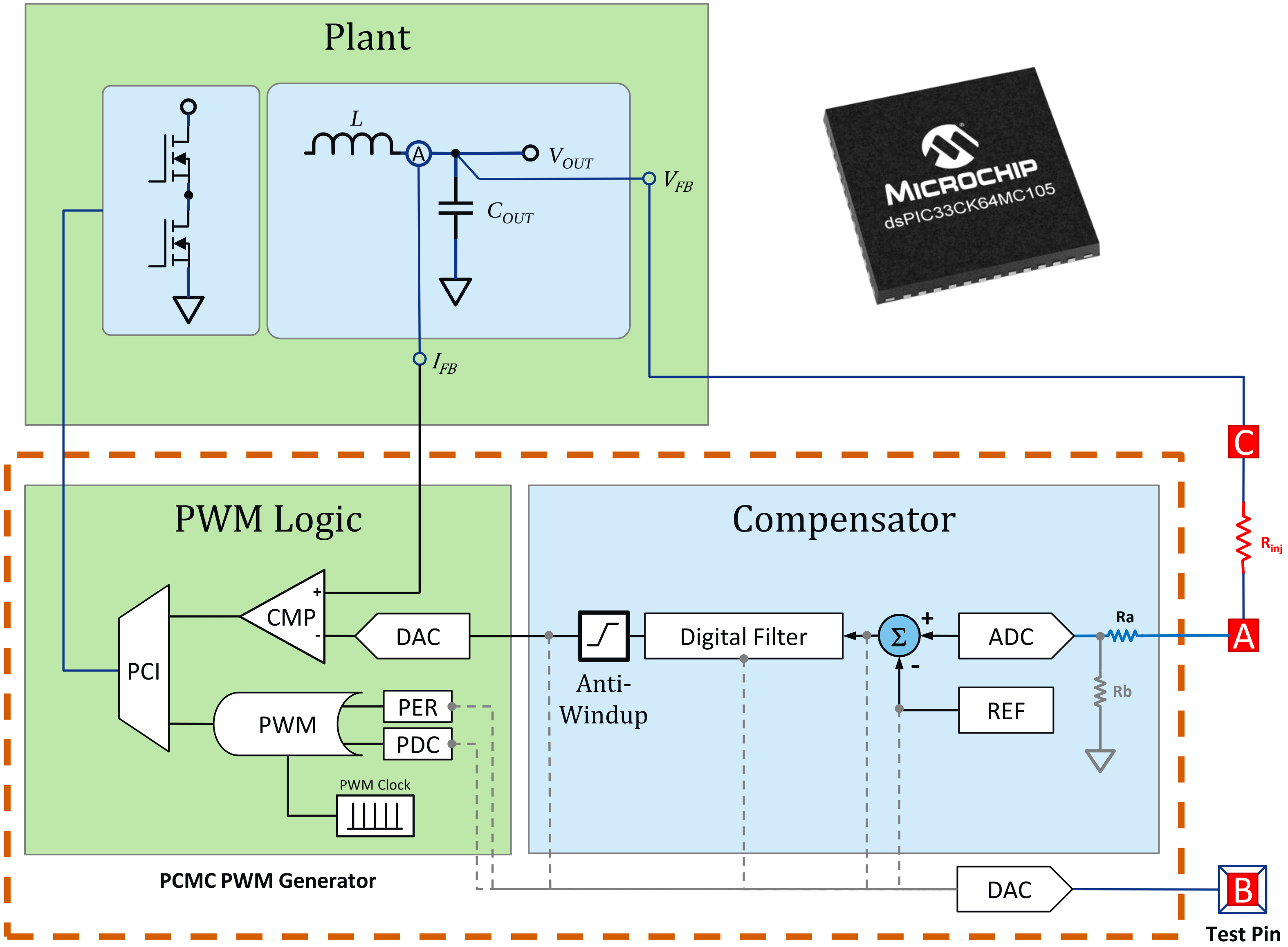
Programmable Analog PWM Controller Access Points

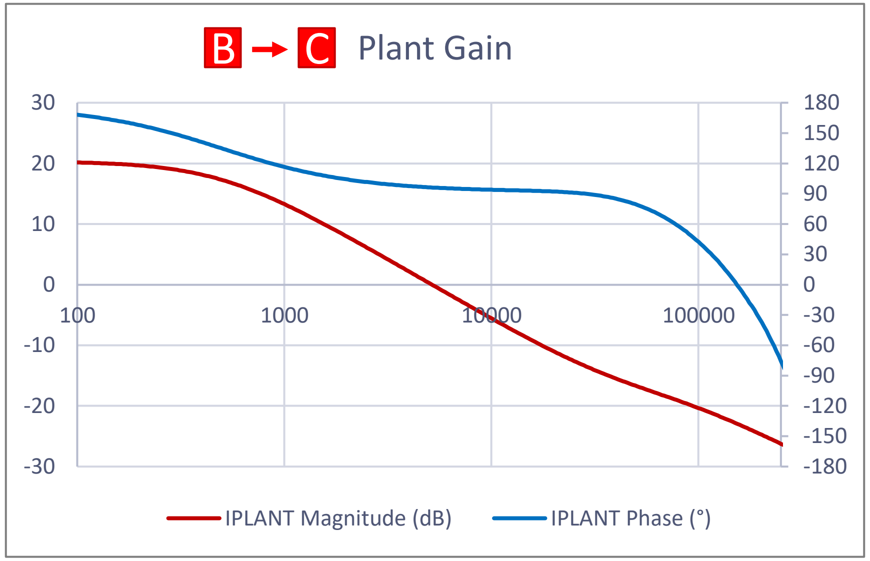


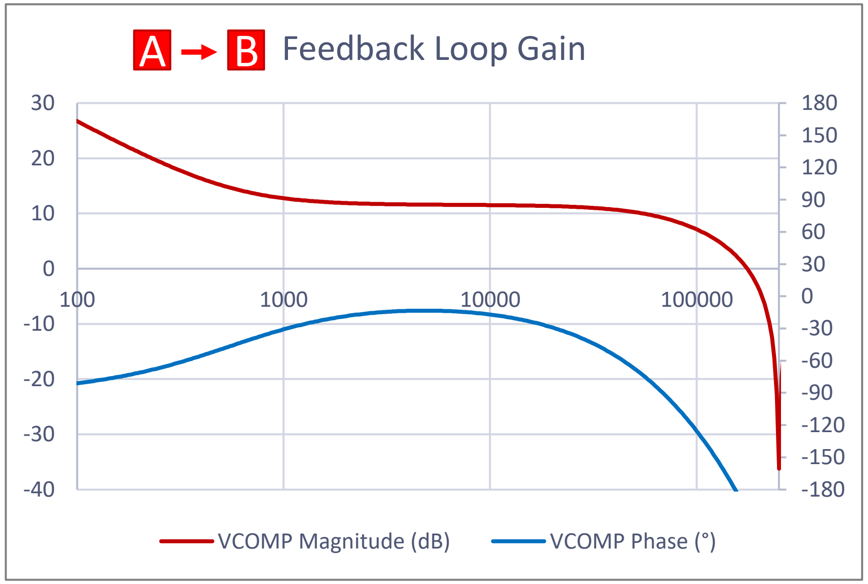




Digital PWM Controller Access Points







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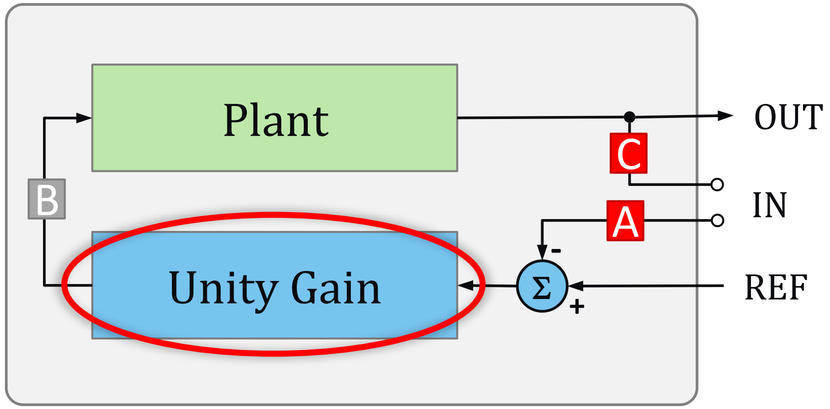
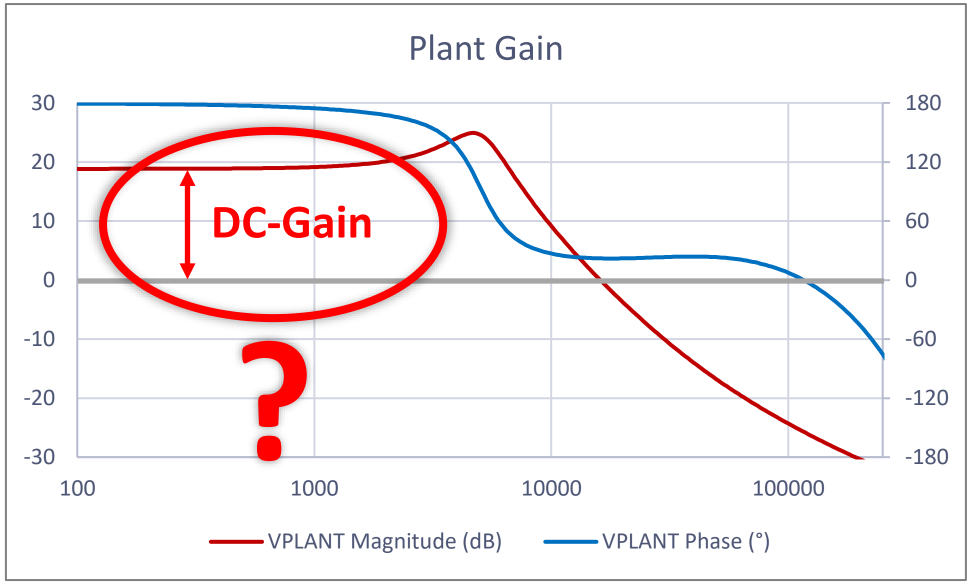
Constant Gain Feedback Loop



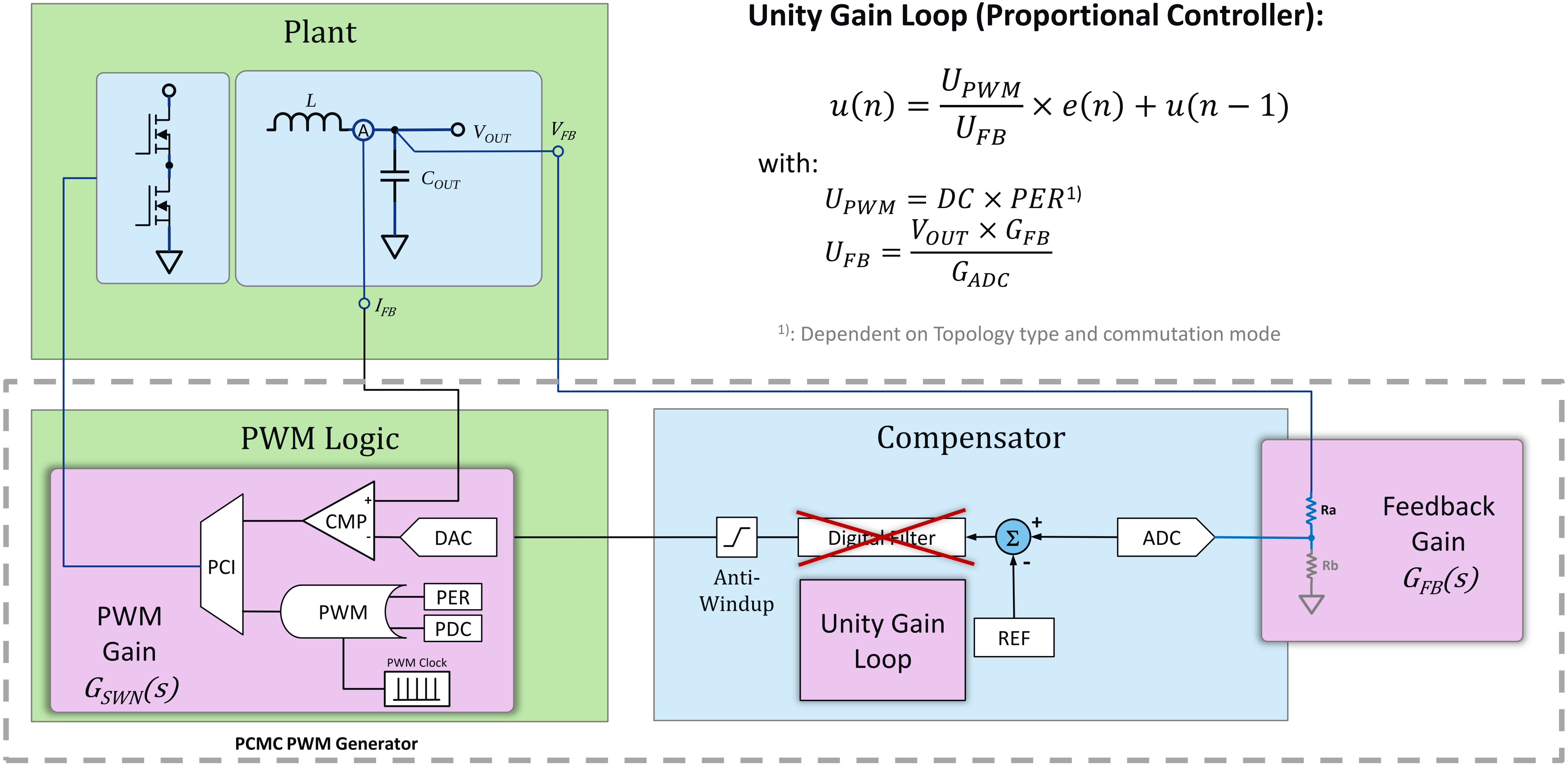
$$G_{OL}(s) = G(s) \times 1$$

$$G_{OL}(s) = G(s)$$



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

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

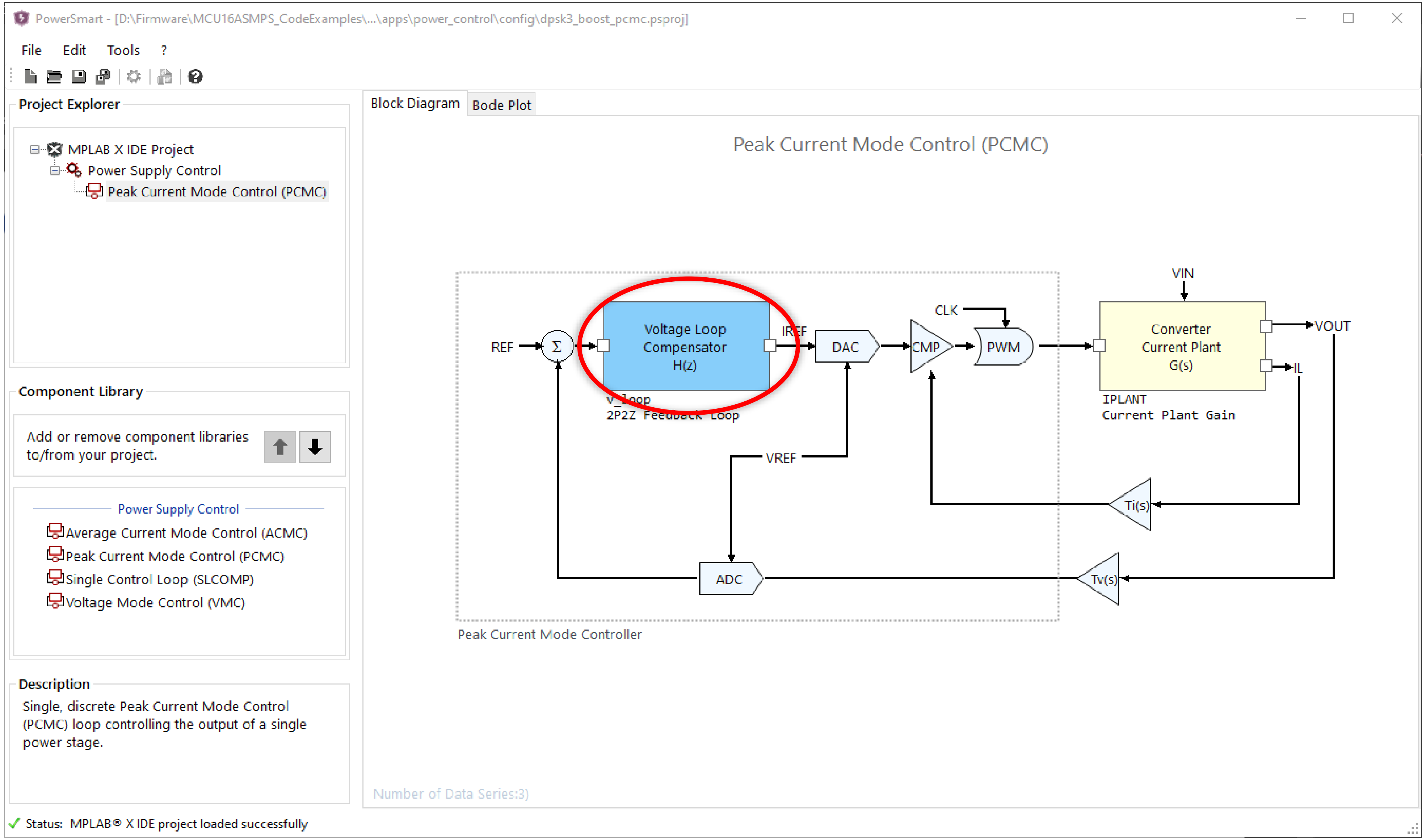
2. $\mathrm{U_{FB}} = V_{OUT} \times \frac{\mathrm{G_{FB}}}{\mathrm{G_{ADC}}} = 15\ V \times \frac{0.125\,\frac{V}{V}}{805.7 \times 10^{-6}\frac{V}{tick}} = 2{,}333\ ticks$

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

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

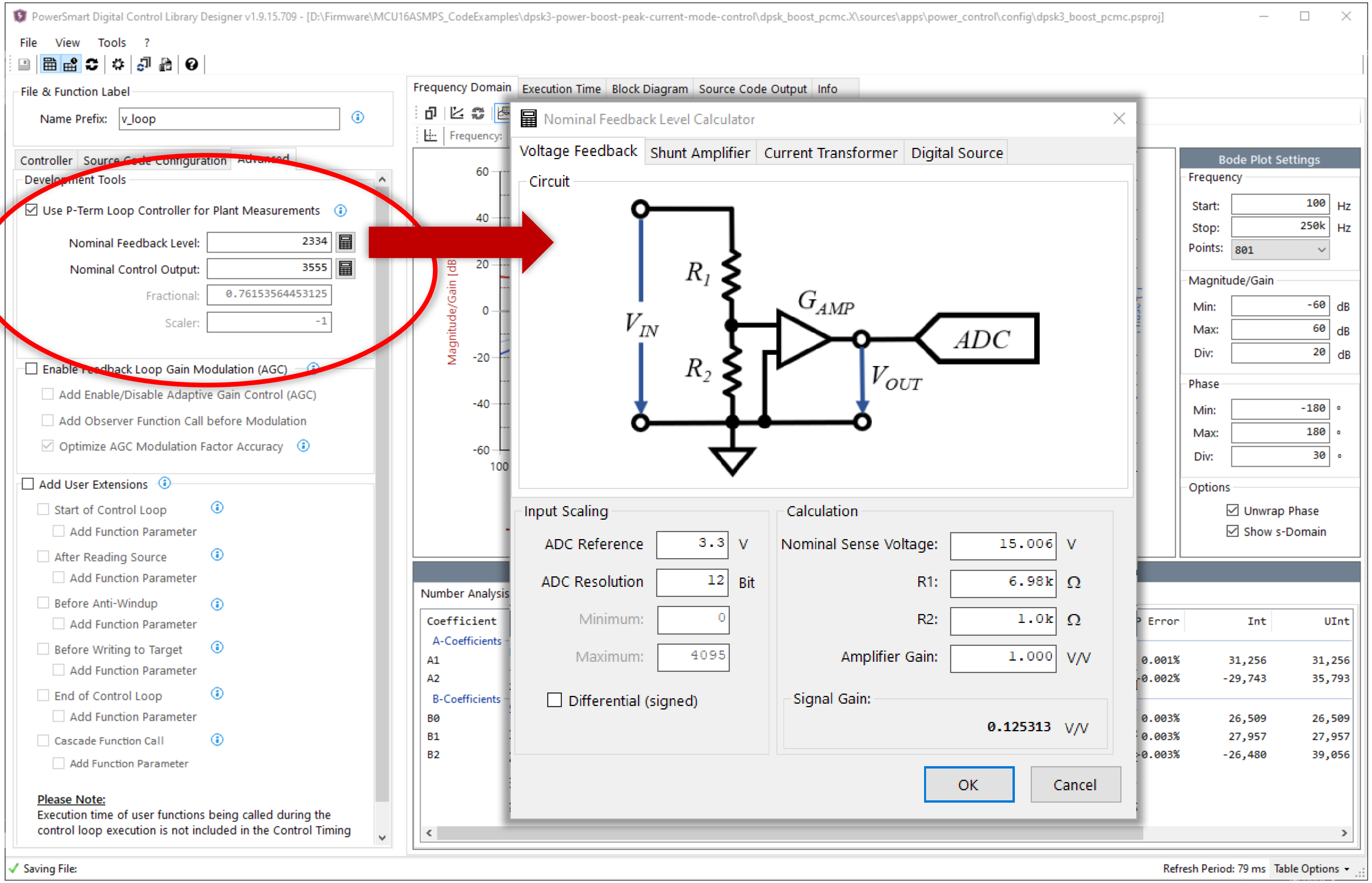
$$k = \frac{U_{PWM}}{U_{FB}} = \frac{3{,}556\ ticks}{2{,}333\ ticks} = 1.524027$$

Deriving Parameters using MPLAB® PowerSmart™



https://www.microchip.com/PowerSmart

Deriving Parameters using MPLAB® PowerSmart™



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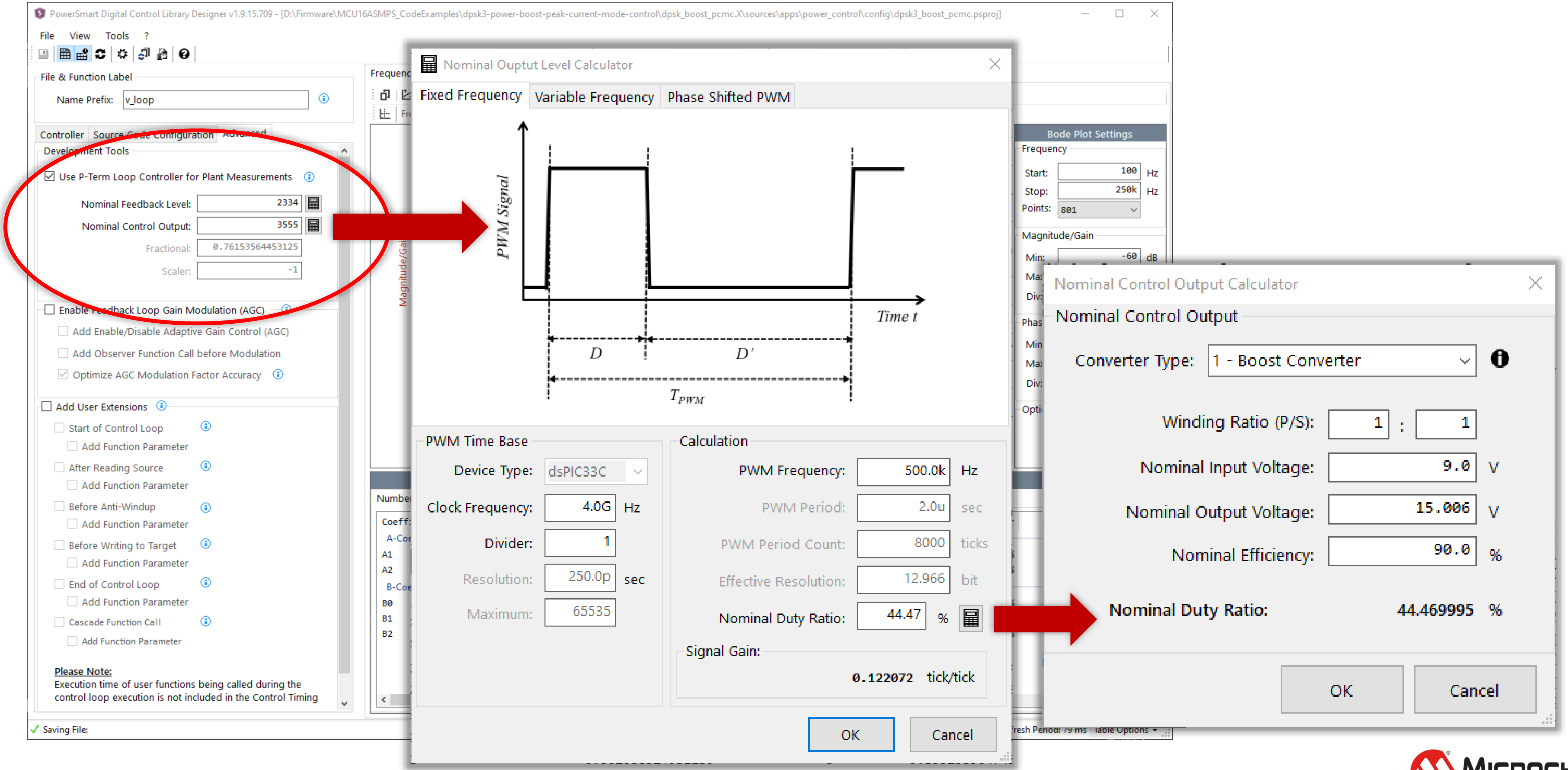

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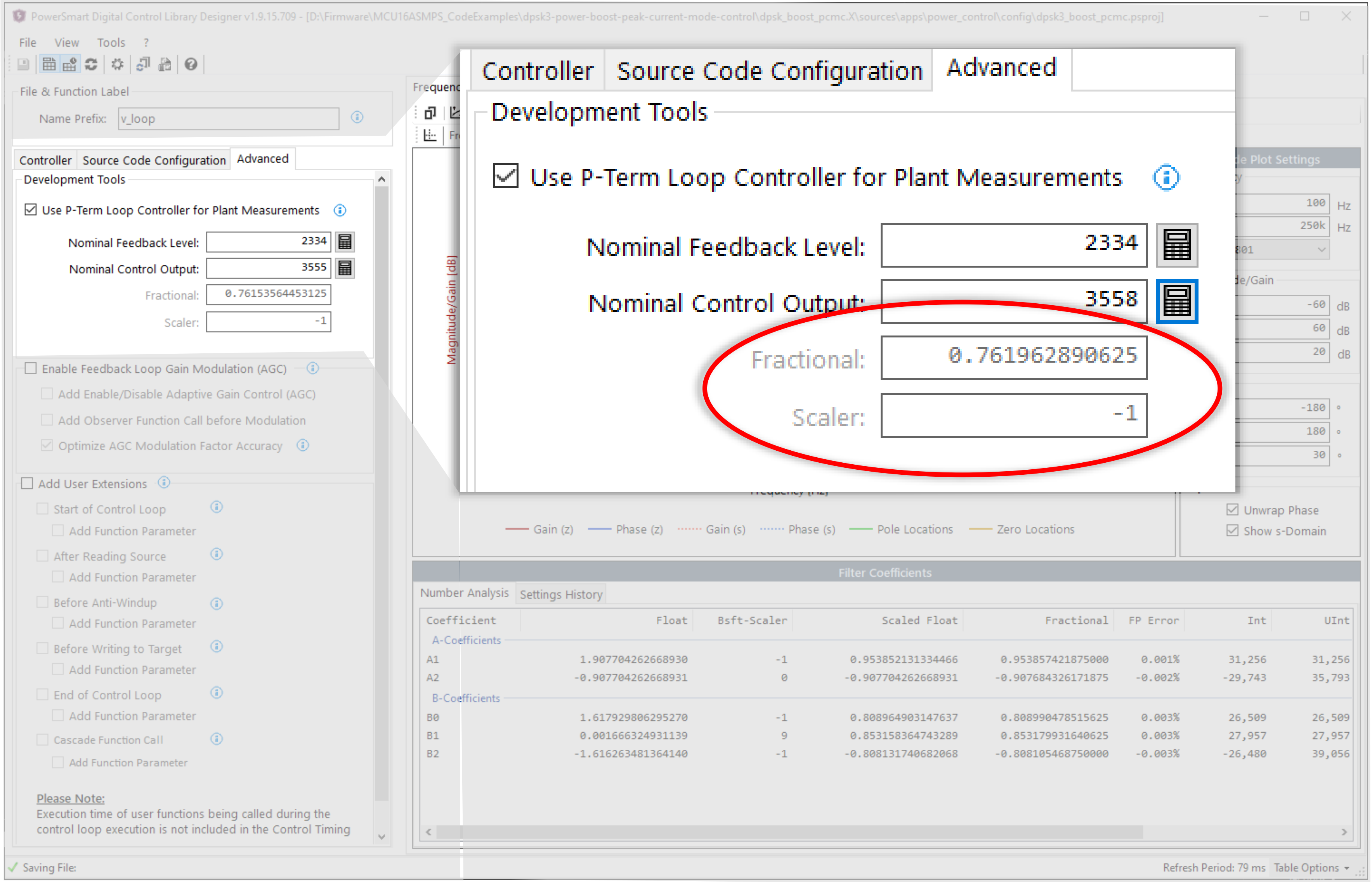

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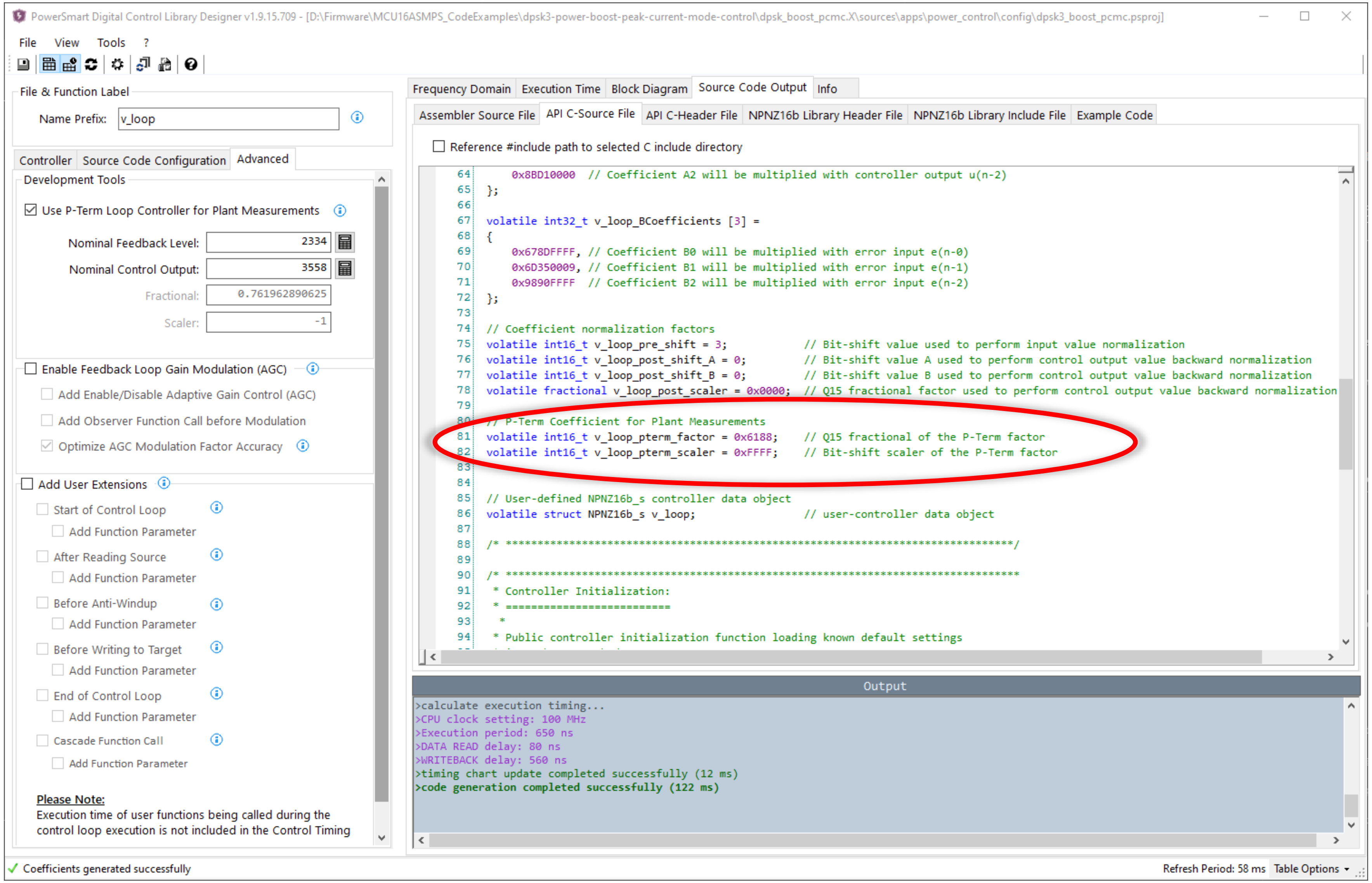

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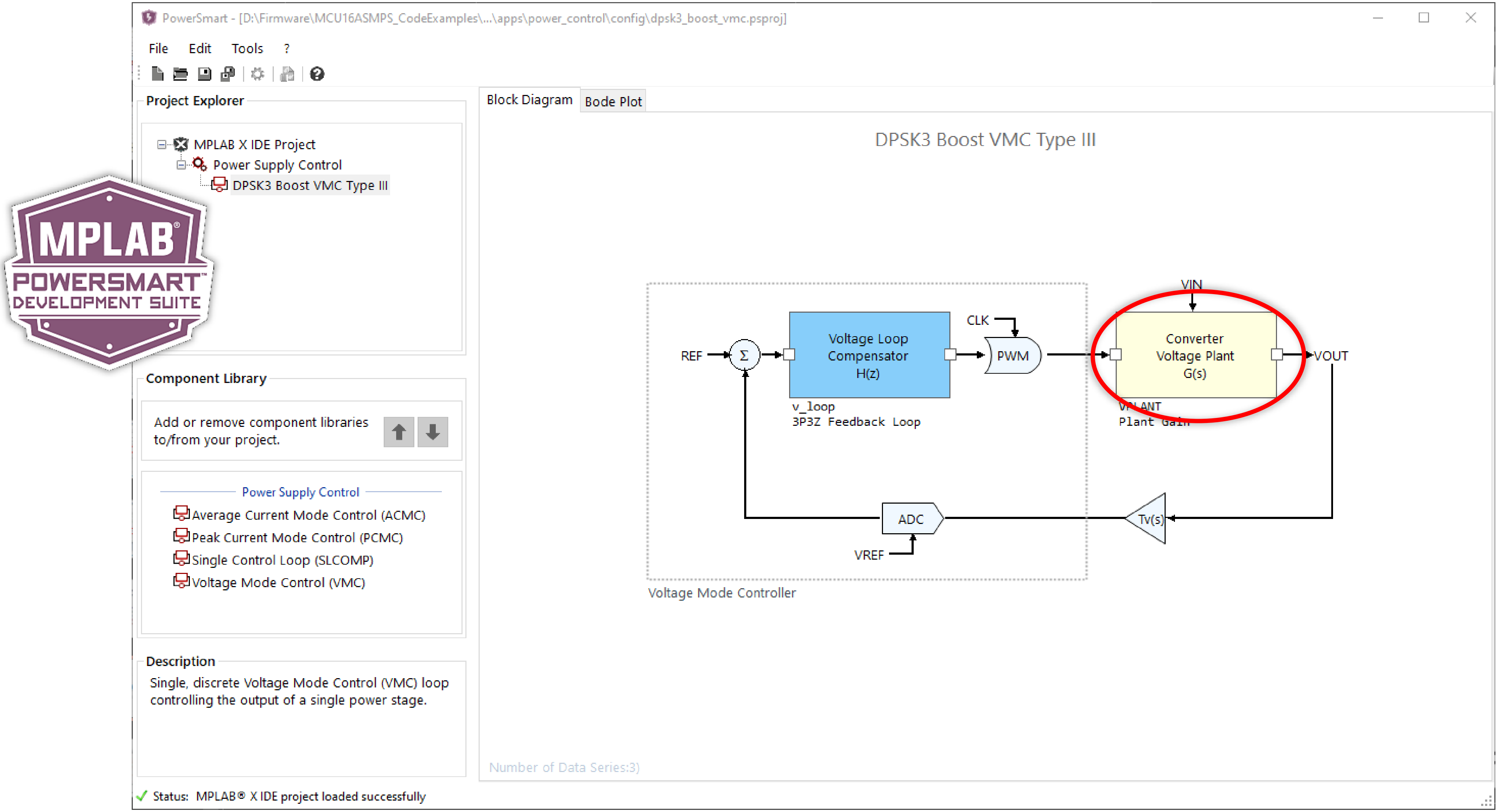
Caution!

- **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



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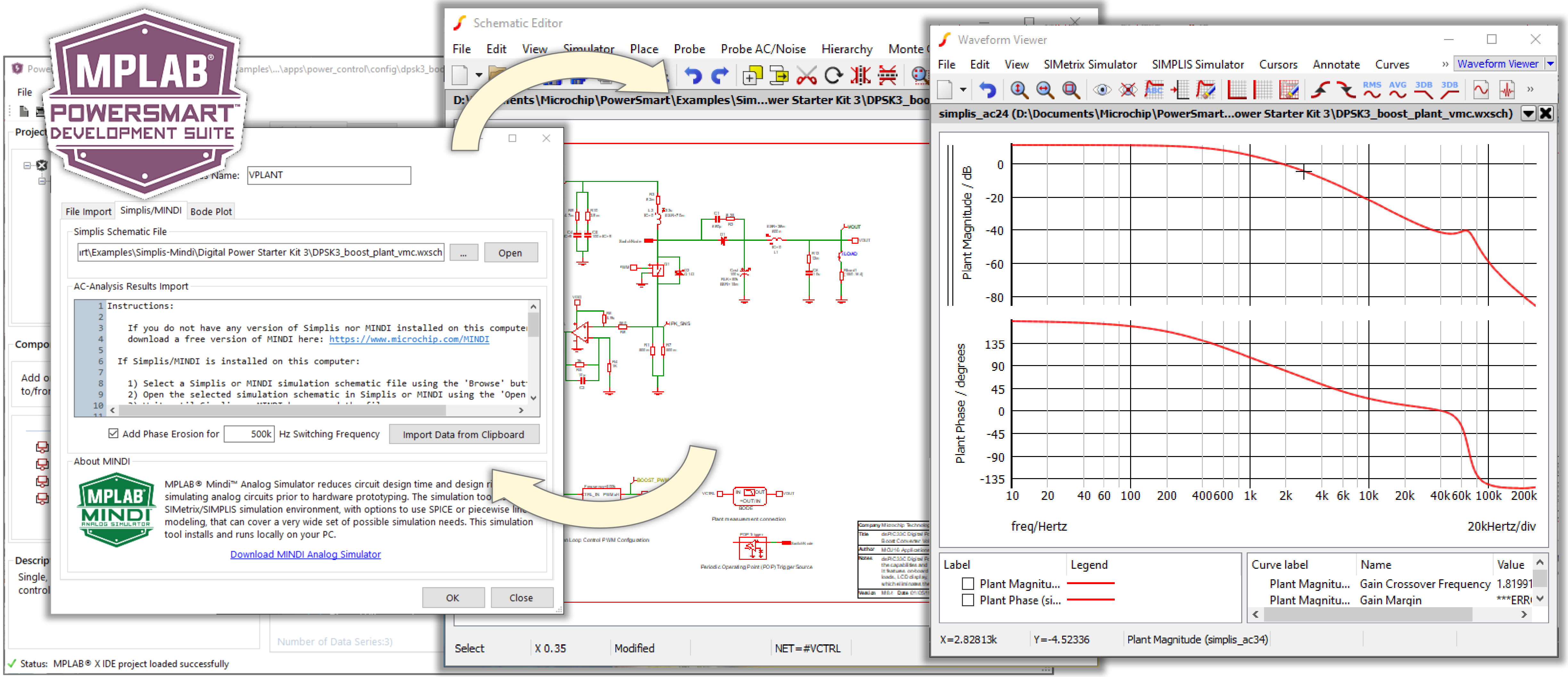
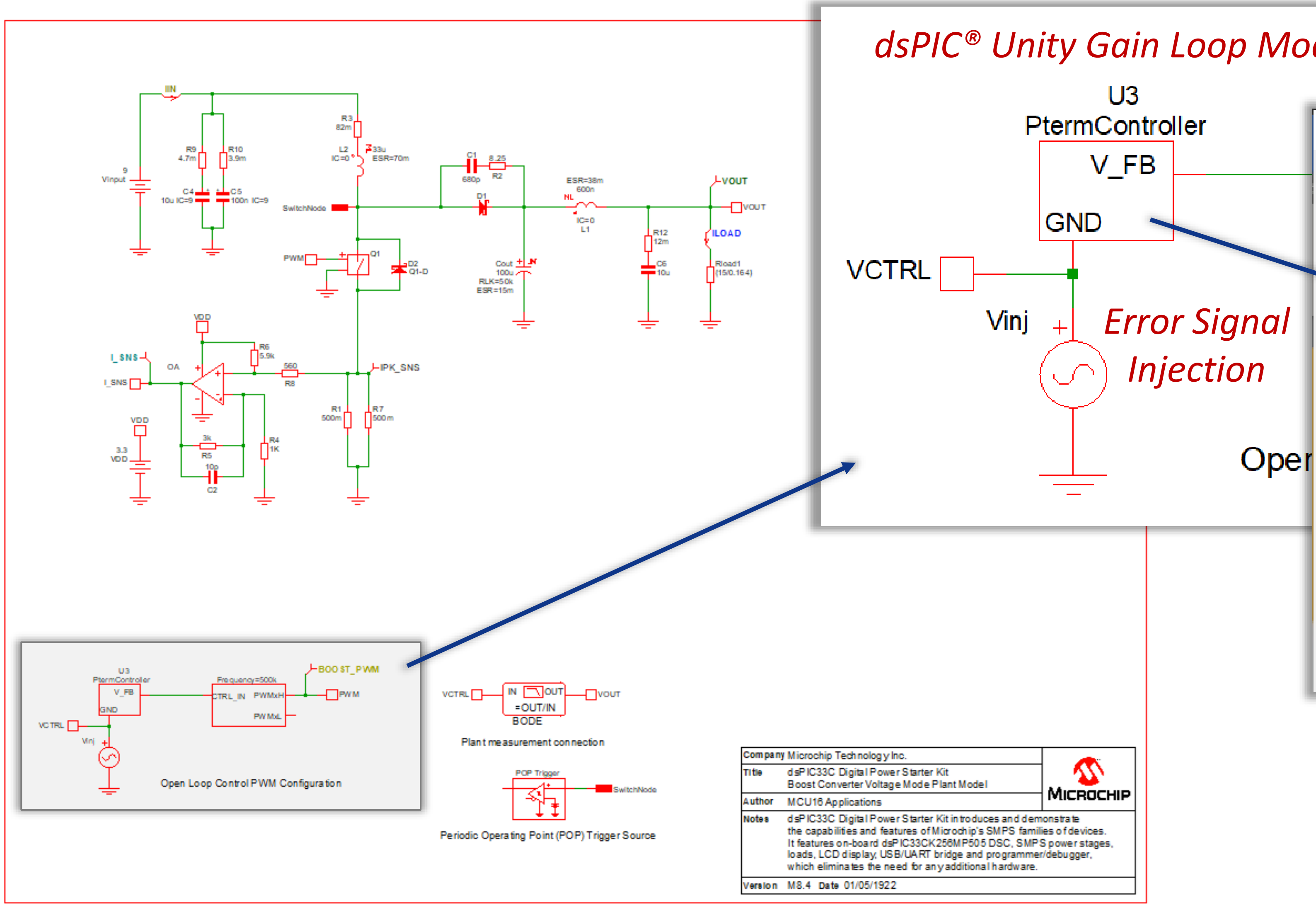
Circuit Simulation

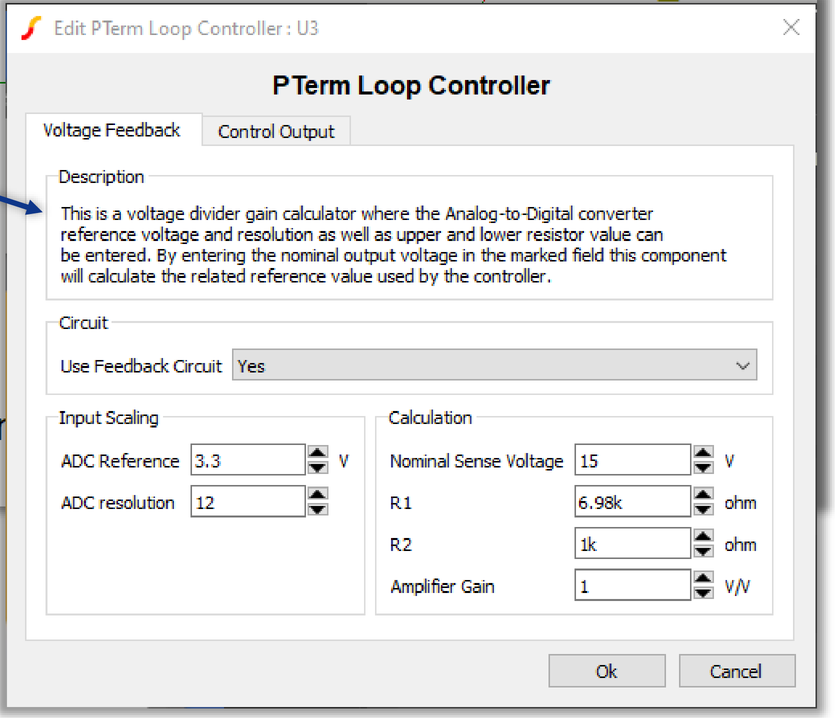
Plant import from external sources



Circuit Simulation

Simulation matches measurement principle

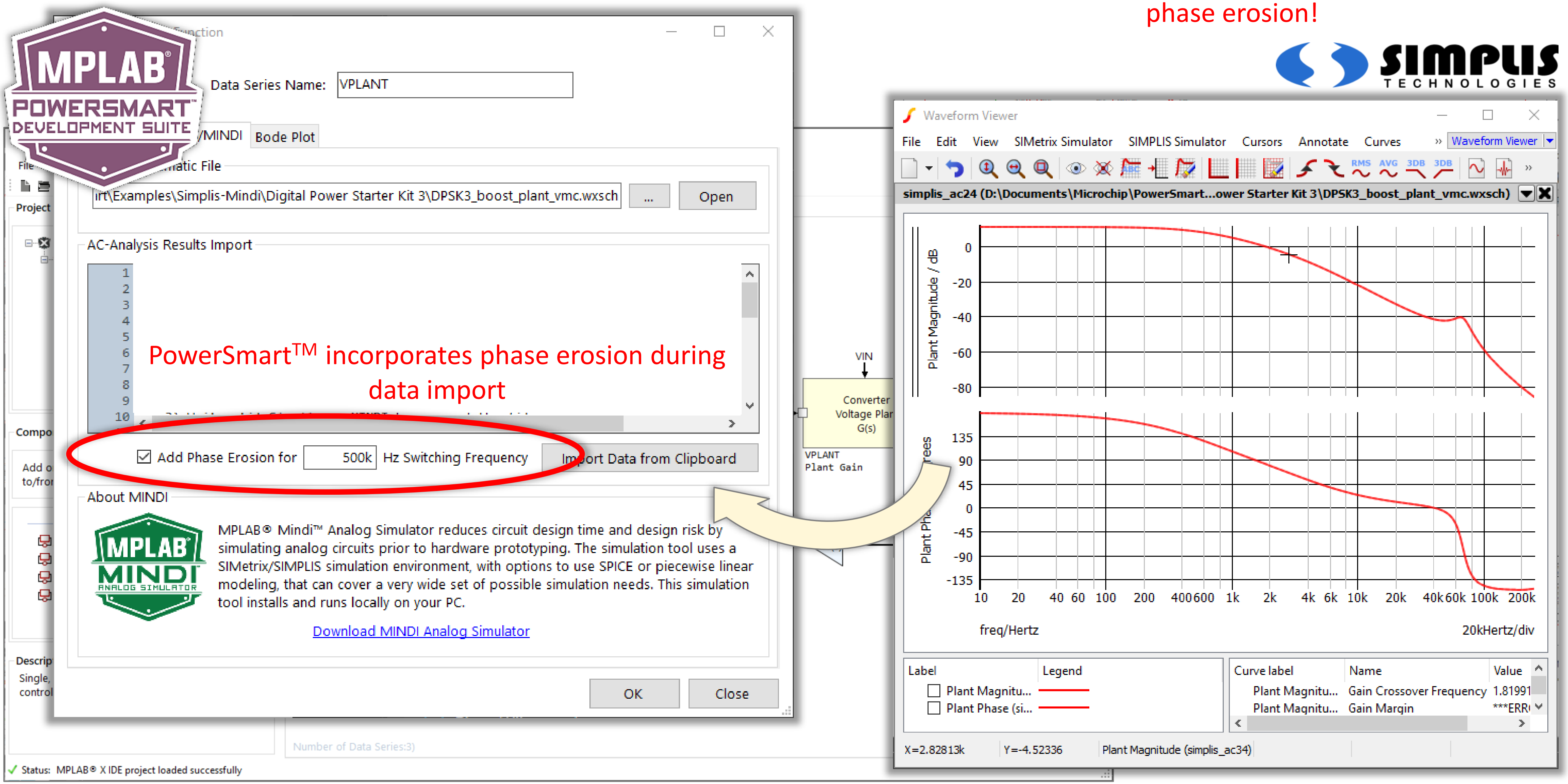




dsPIC® Unity Gain Loop Model Configuration Dialog

Circuit Simulation

SIMPLIS Simulation does not consider switch-state phase erosion!



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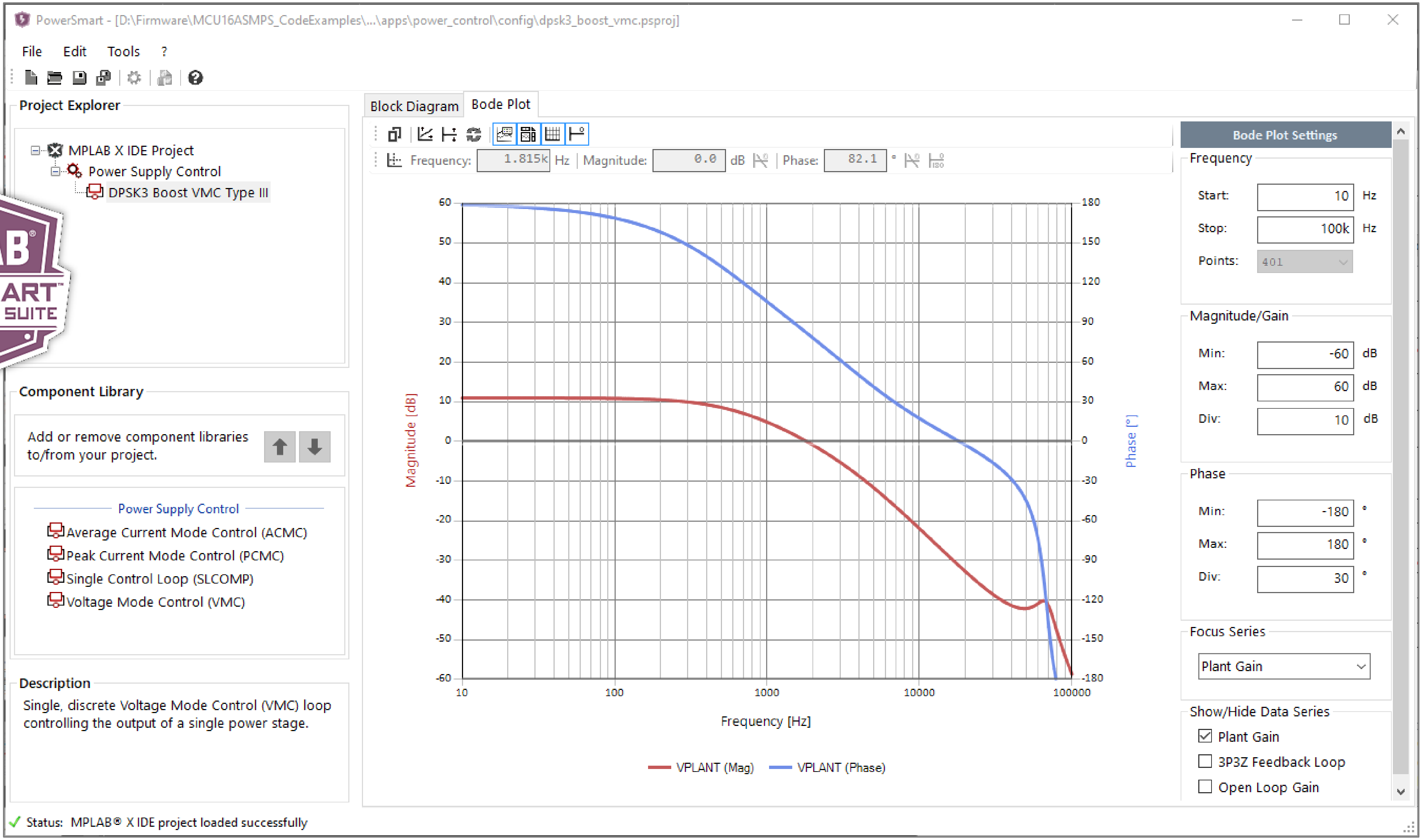
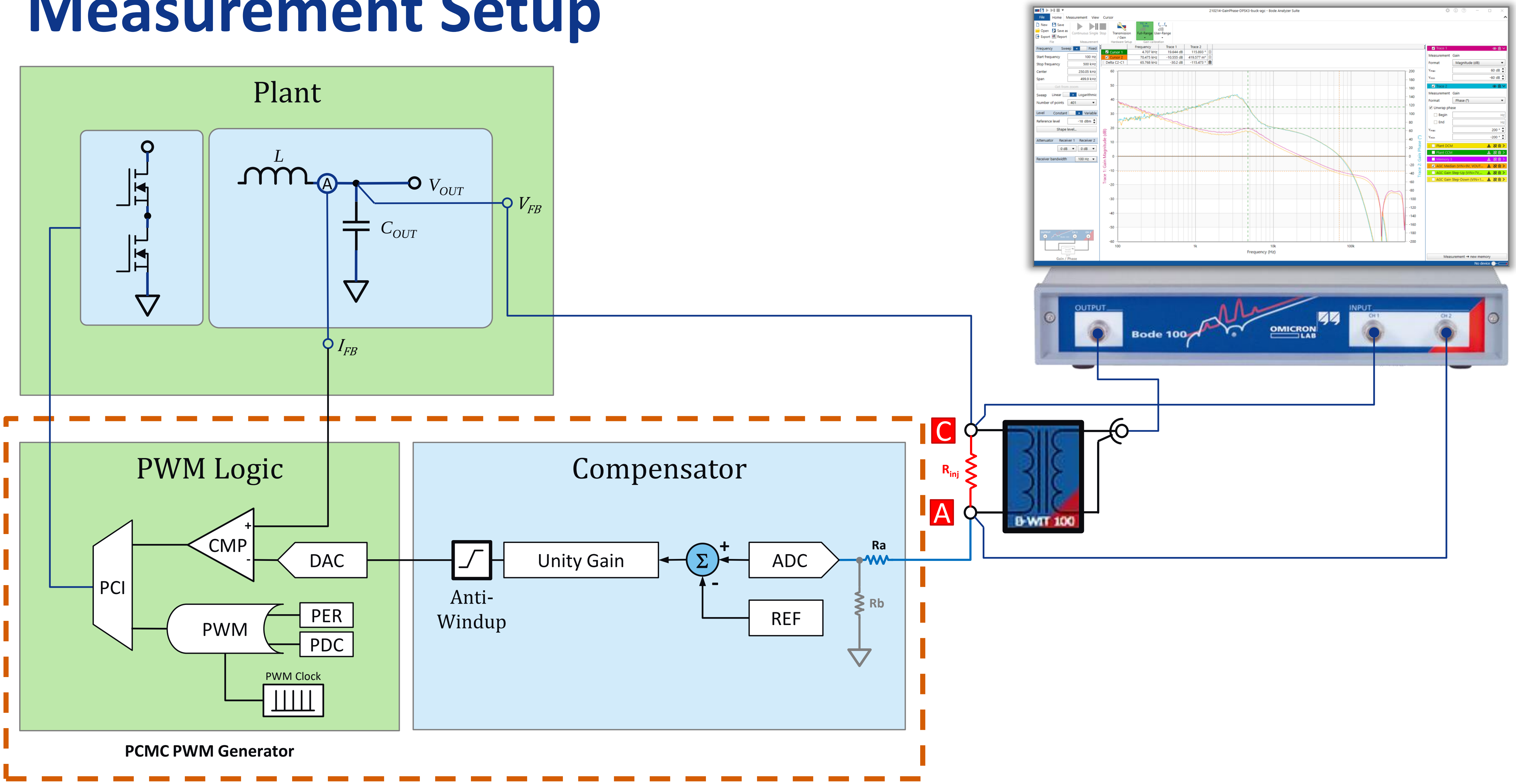
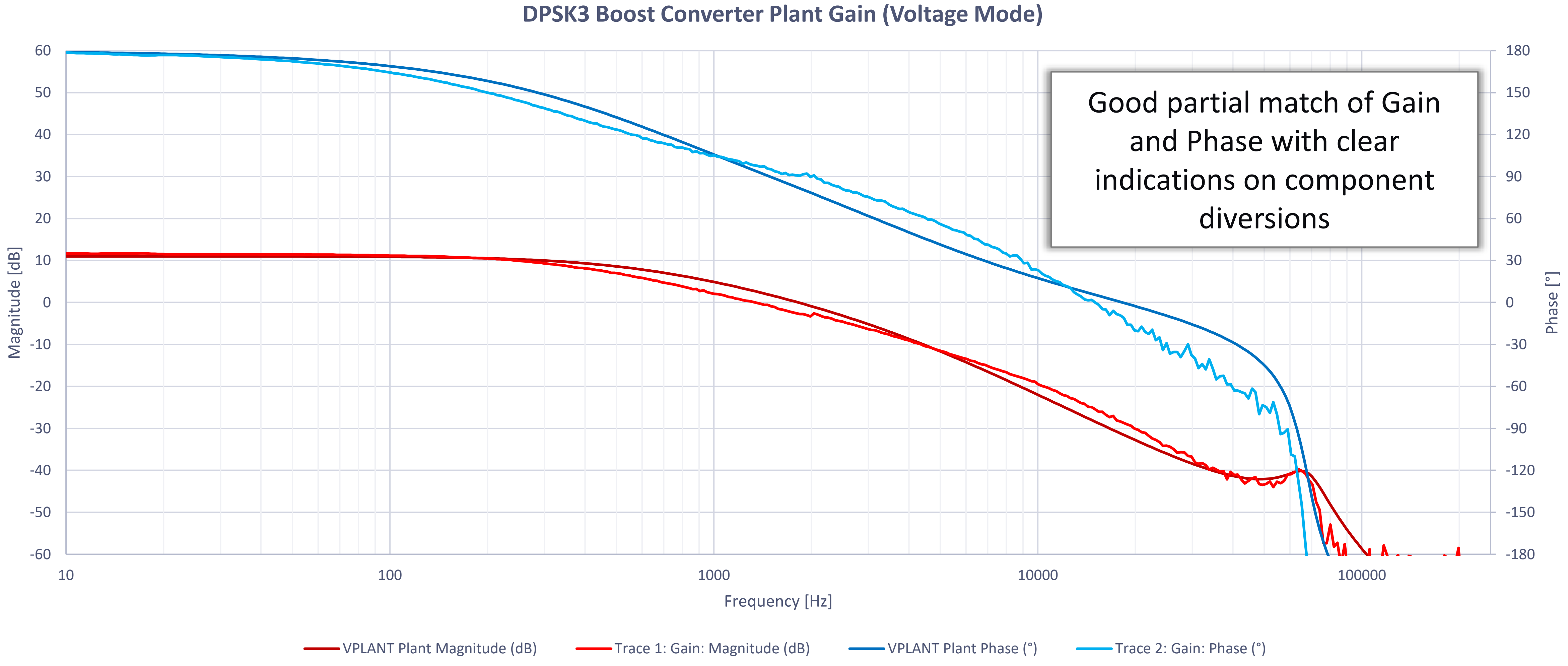


Measurement Setup



Initial Test Results

Simplis Simulation vs. Bench Measurement



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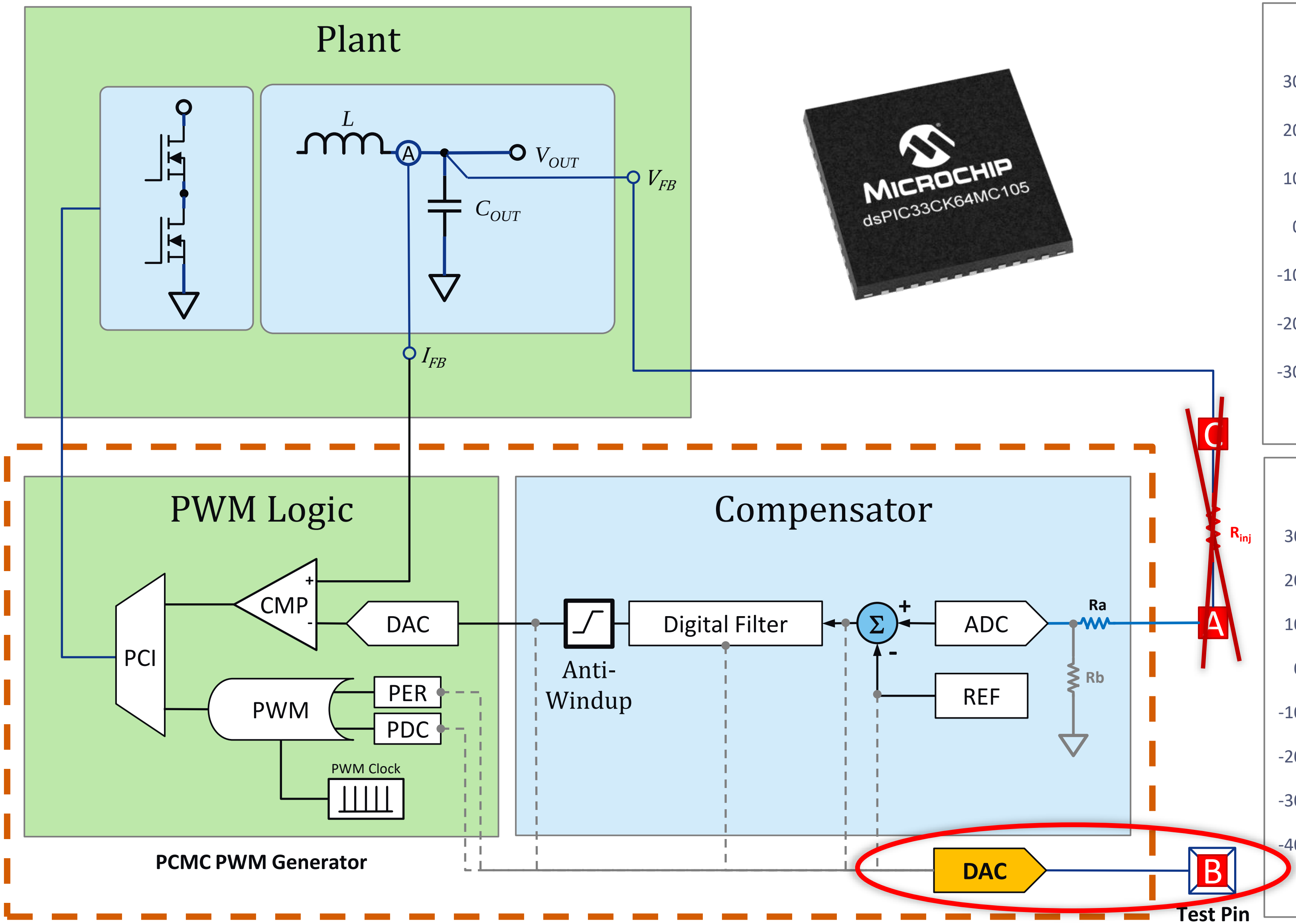
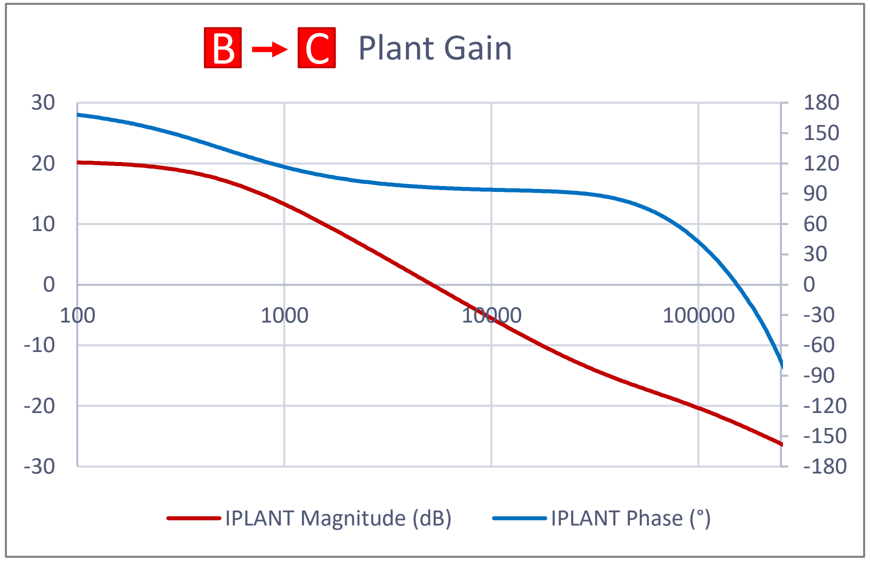
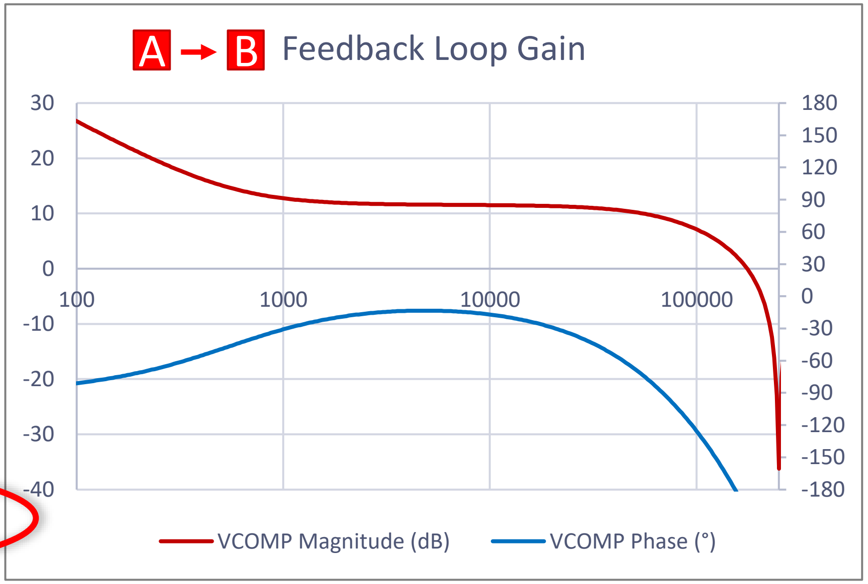
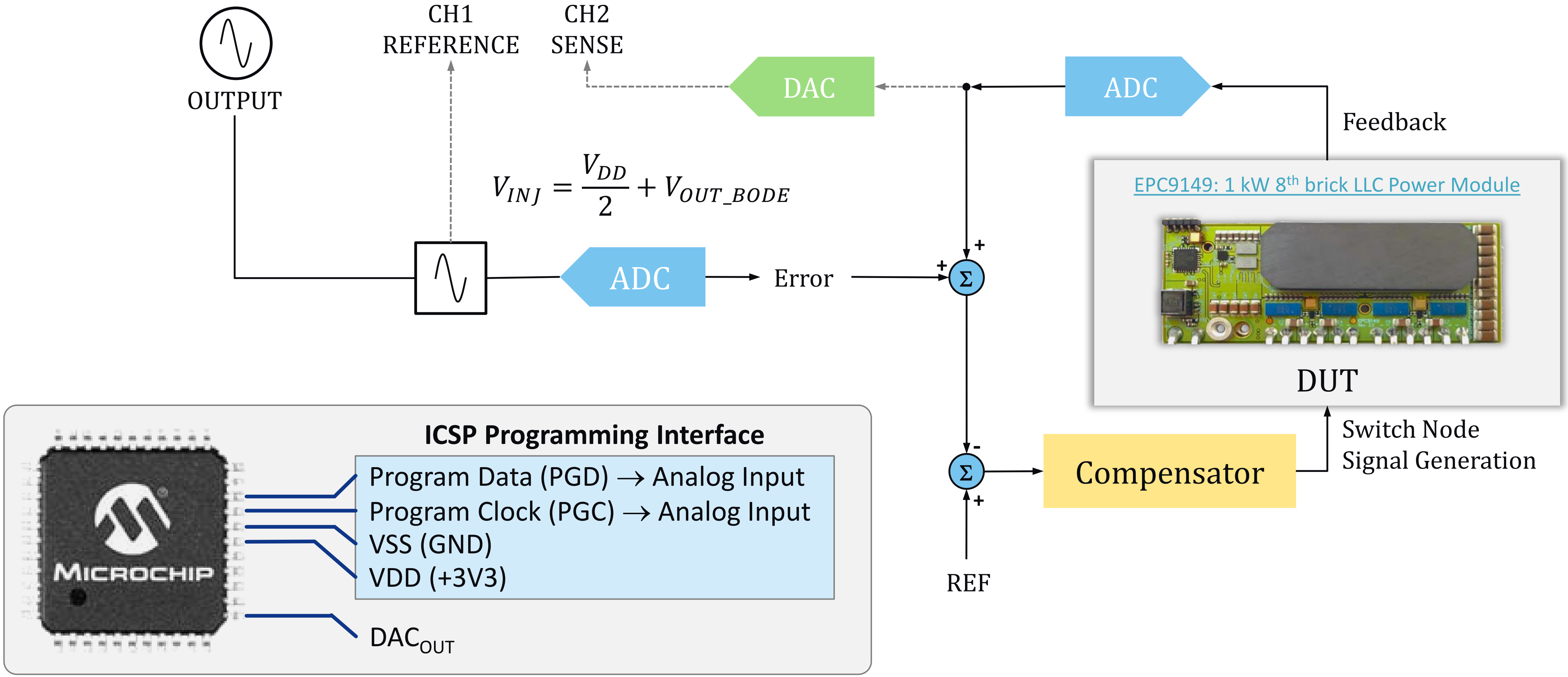
Digital PWM Controller Access Points







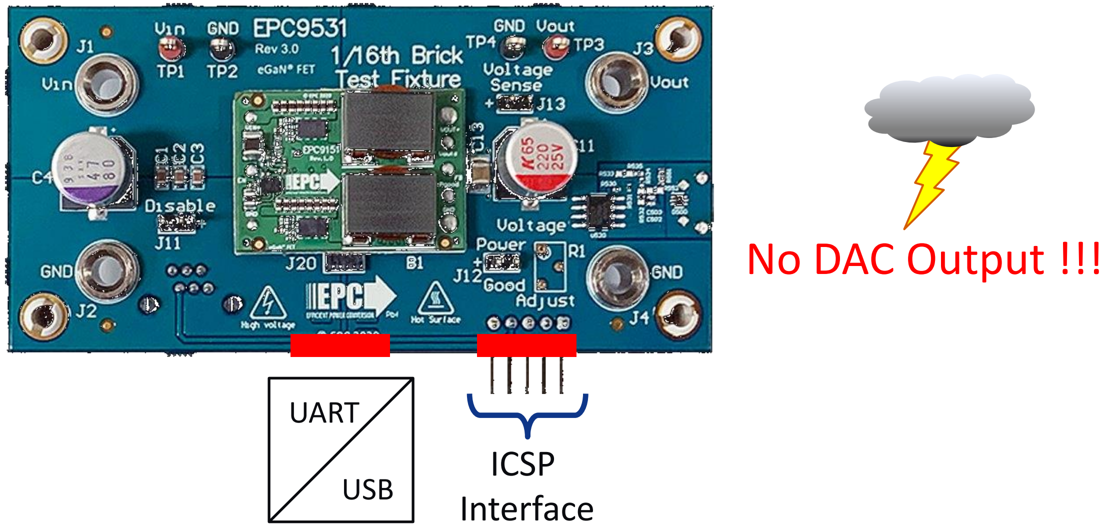
Reusing Available Pins (+1)

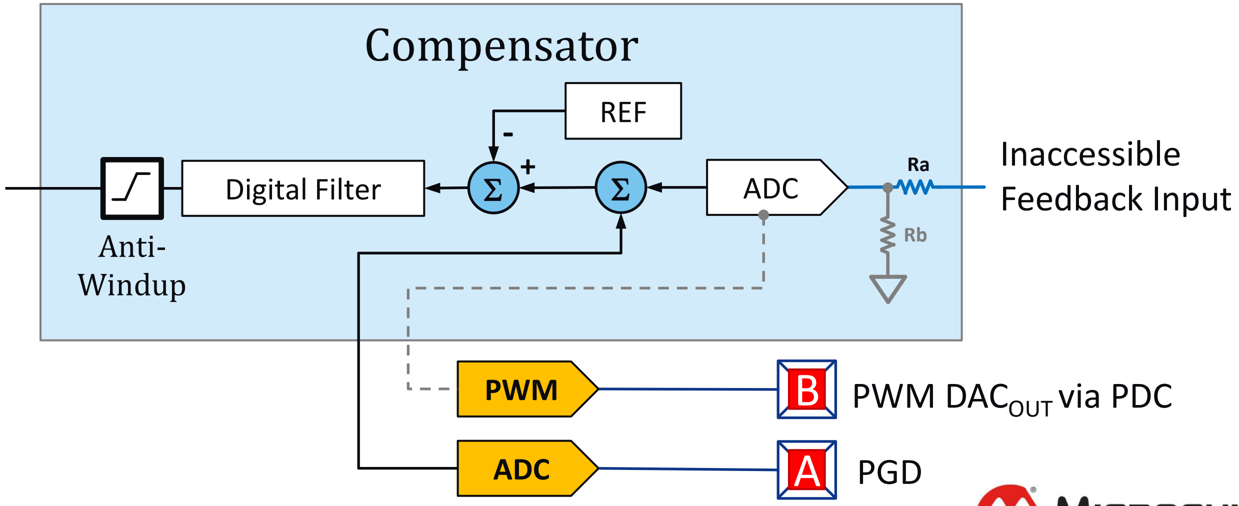


Loop Injection through ICSP

- 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

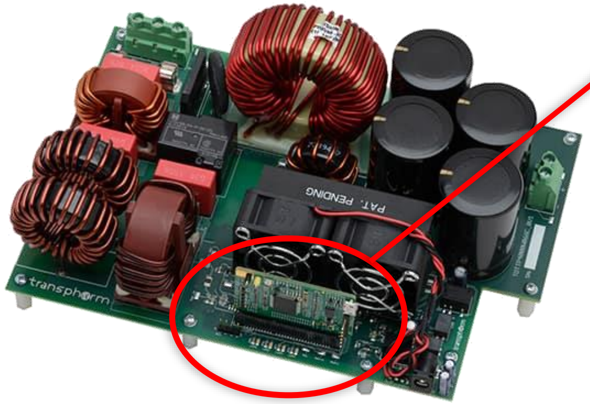


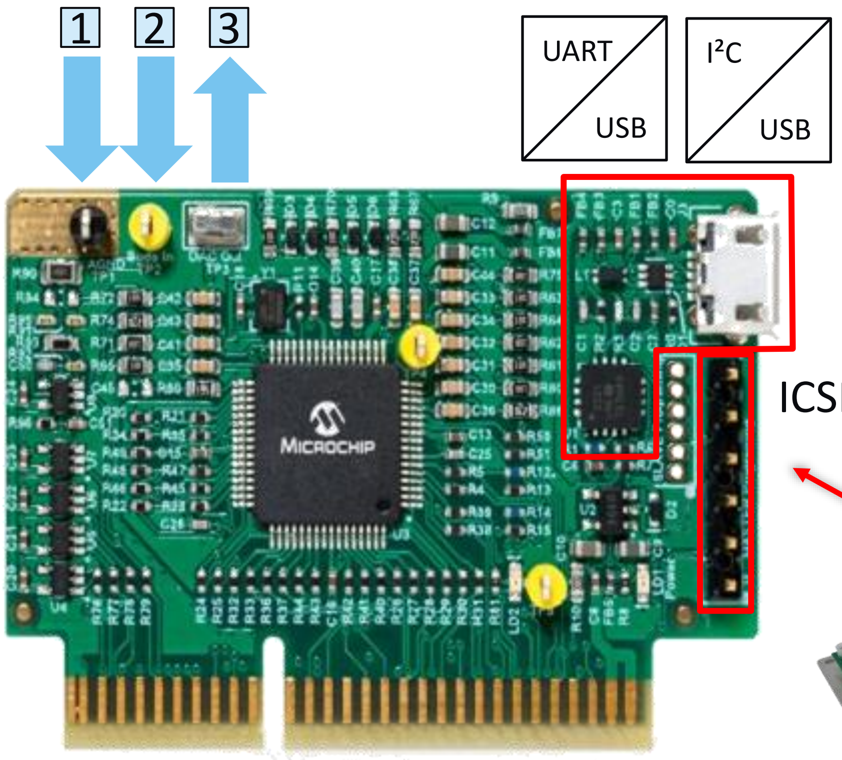


Default Option on CPU Plug-In Boards

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

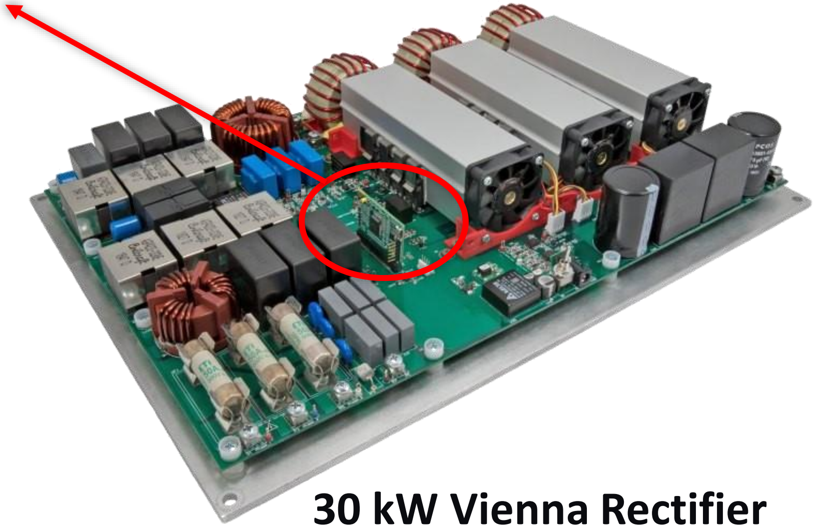
2.5 kW and 4 kW TTP PFC
Transphorm GaN Reference Design





ICSP Programming Interface

Analog I/O
Digital I/O

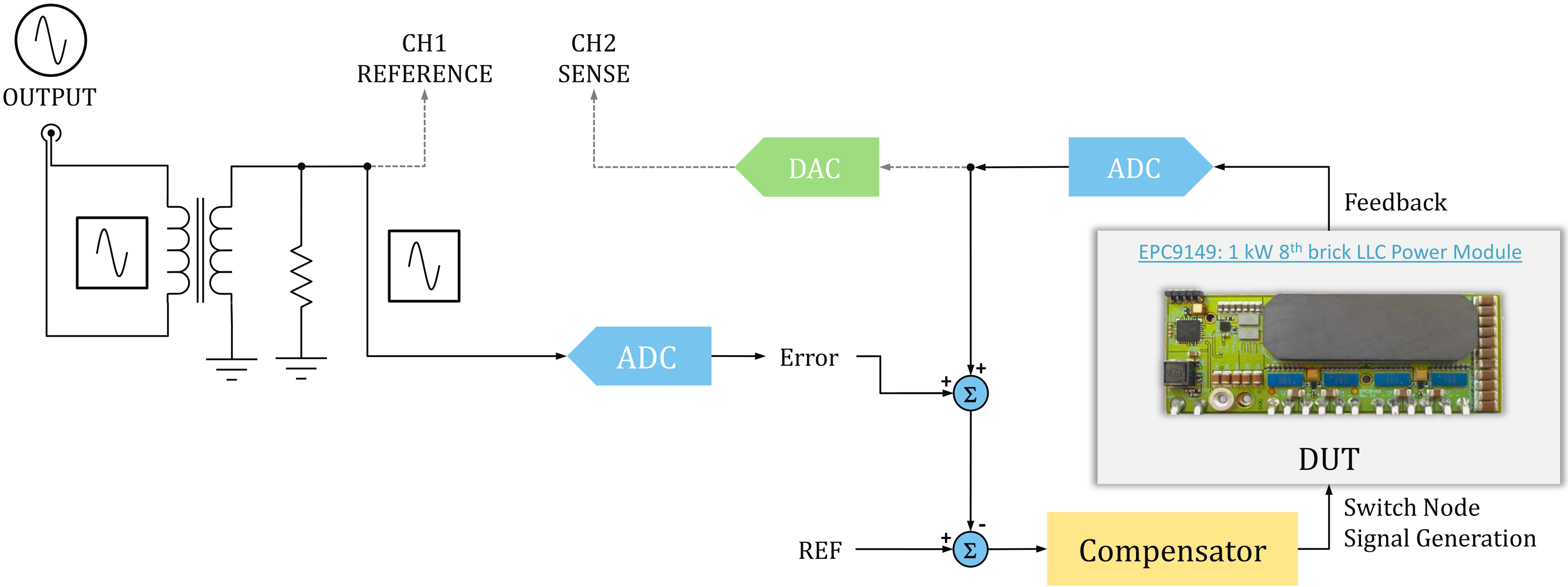


30 kW Vienna Rectifier
MCHP SiC Reference Design

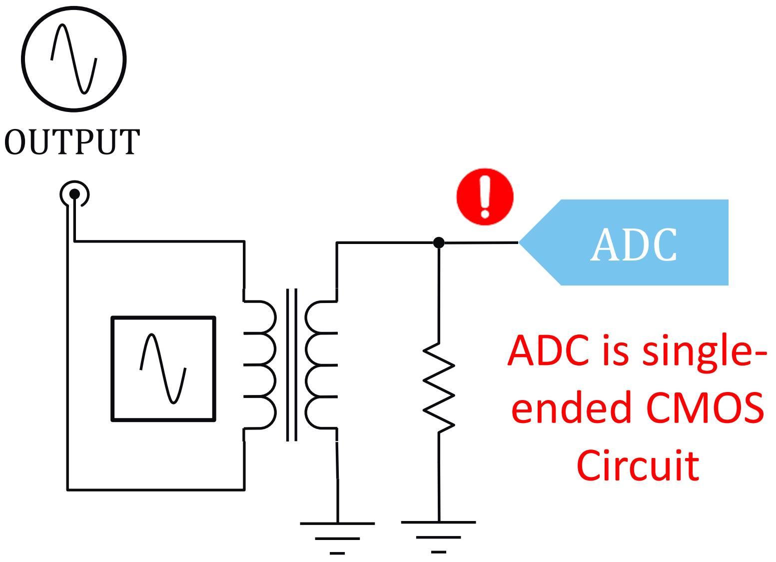
Part-No. Single Core Device: MA330048
Part-No. Dual Core Device: MA330049

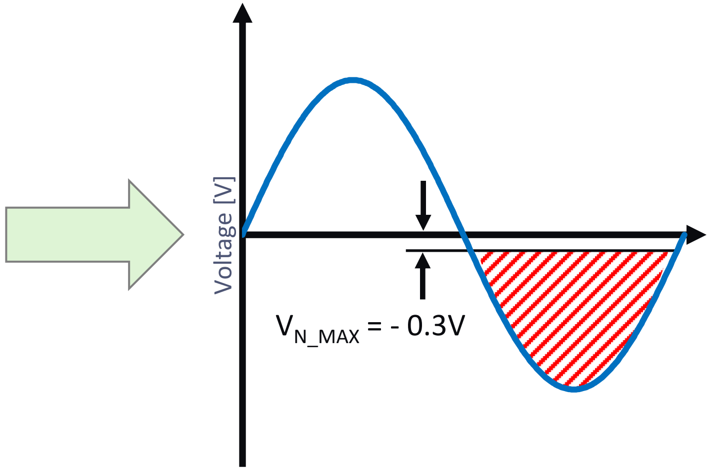
MICROCHIP

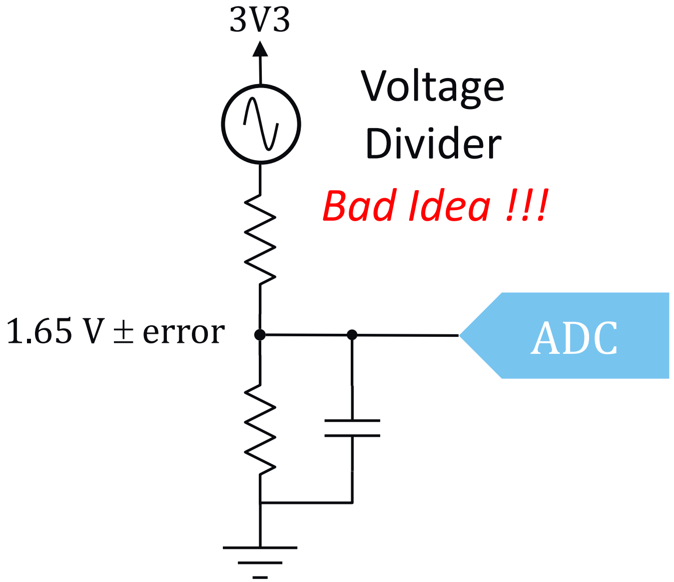
ADC Injection

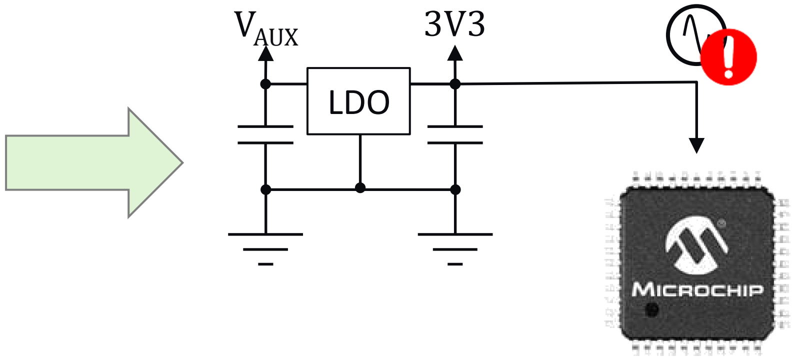


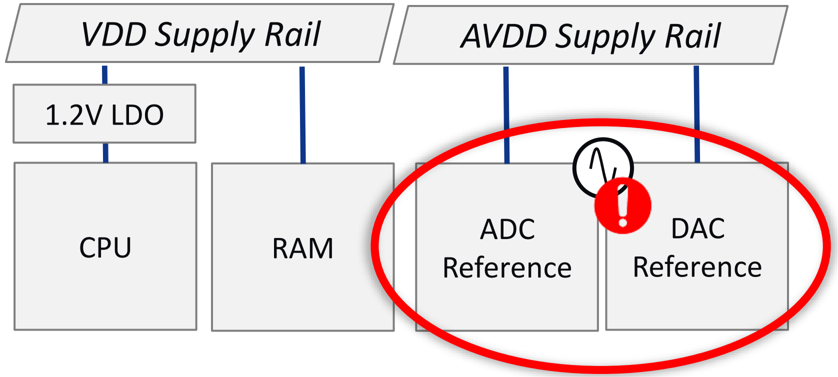
ADC Injection



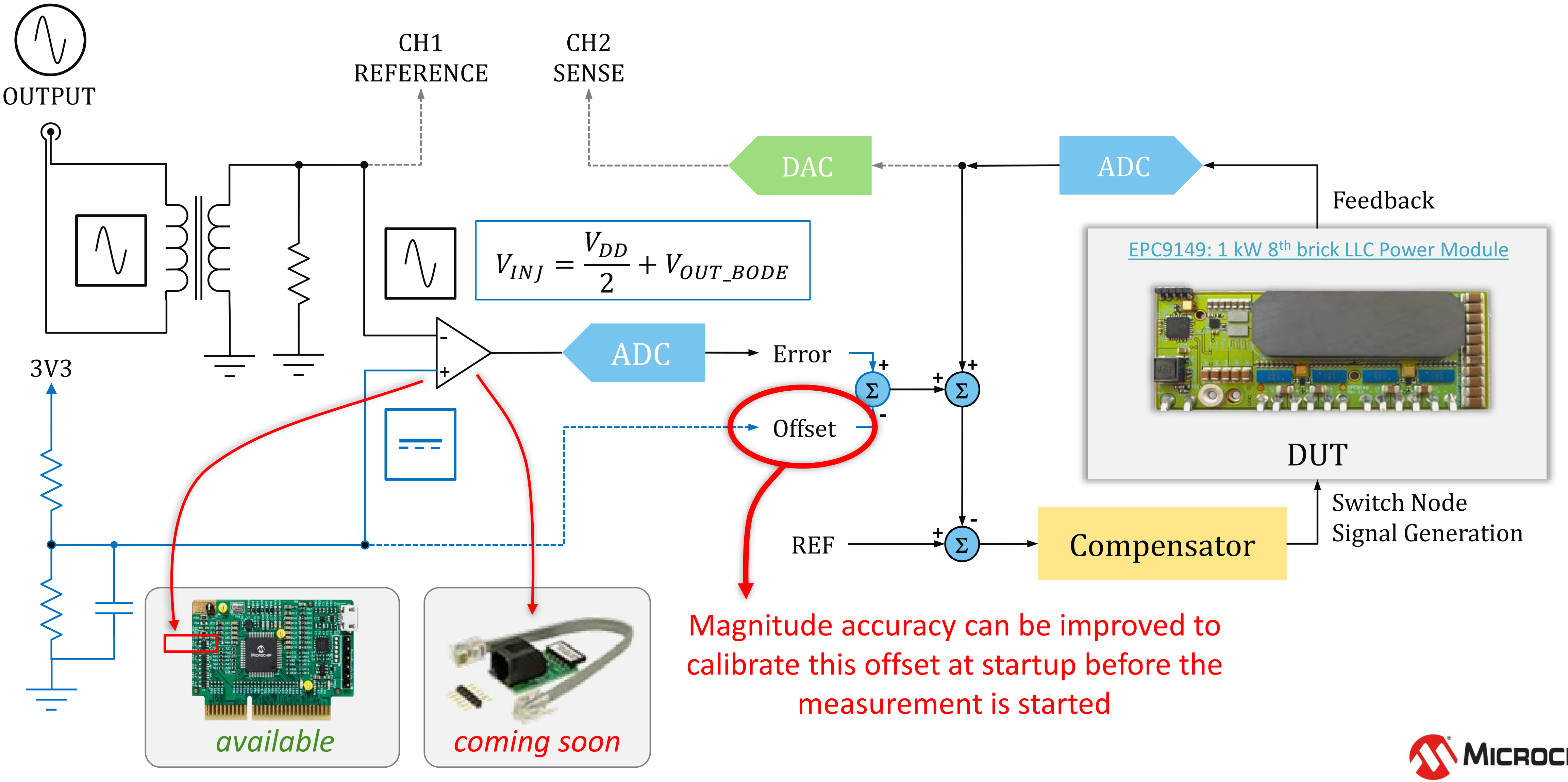








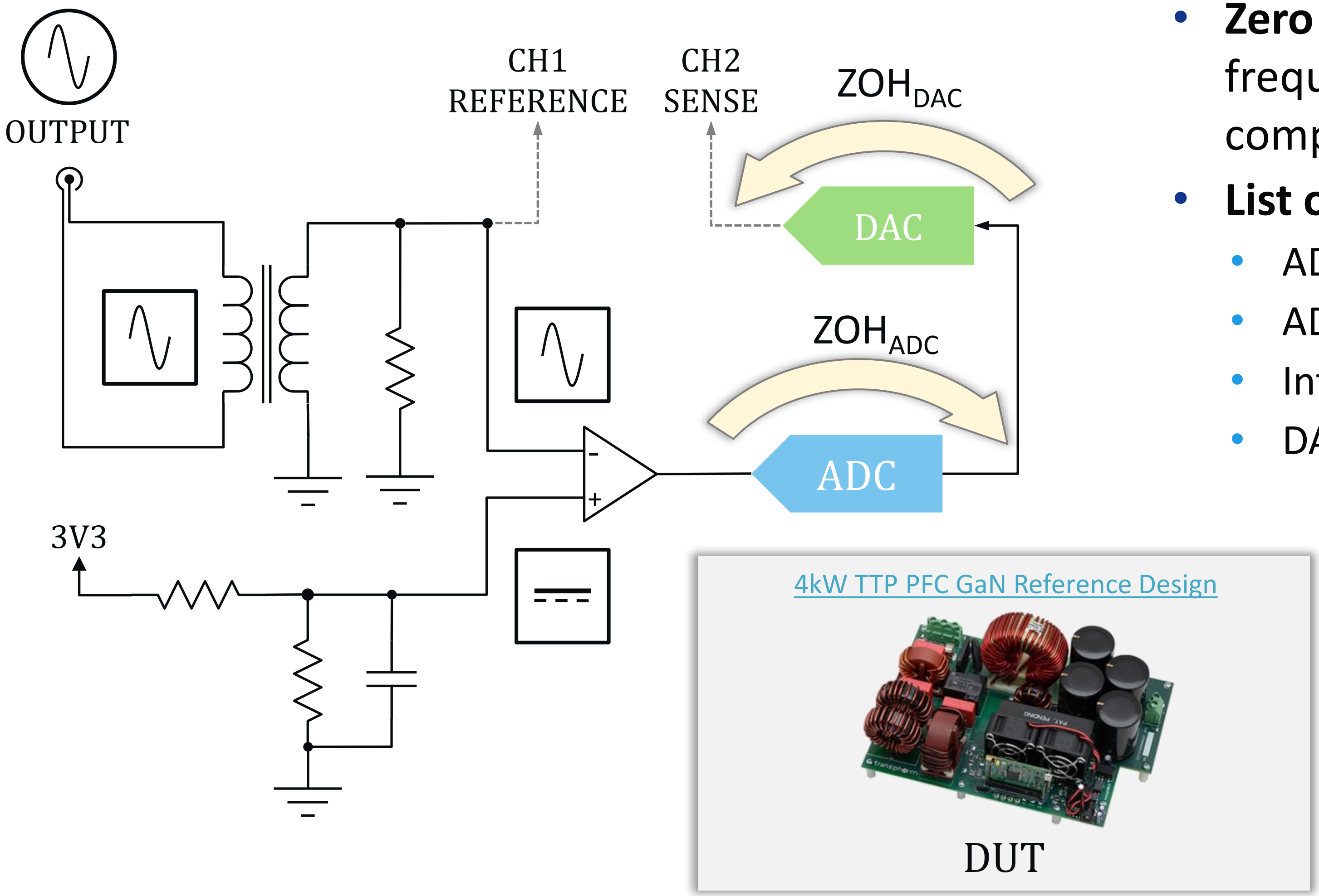
ADC Injection



Magnitude accuracy can be improved to calibrate this offset at startup before the measurement is started

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

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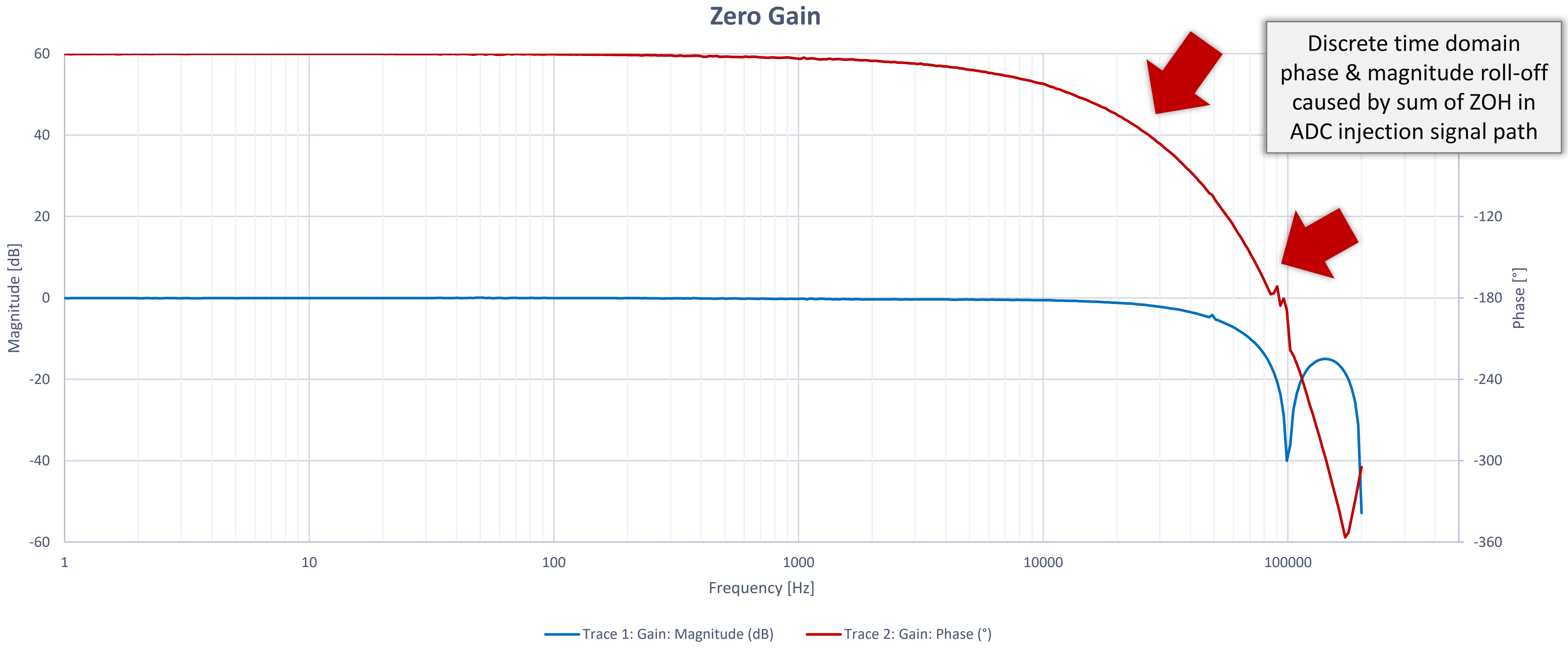
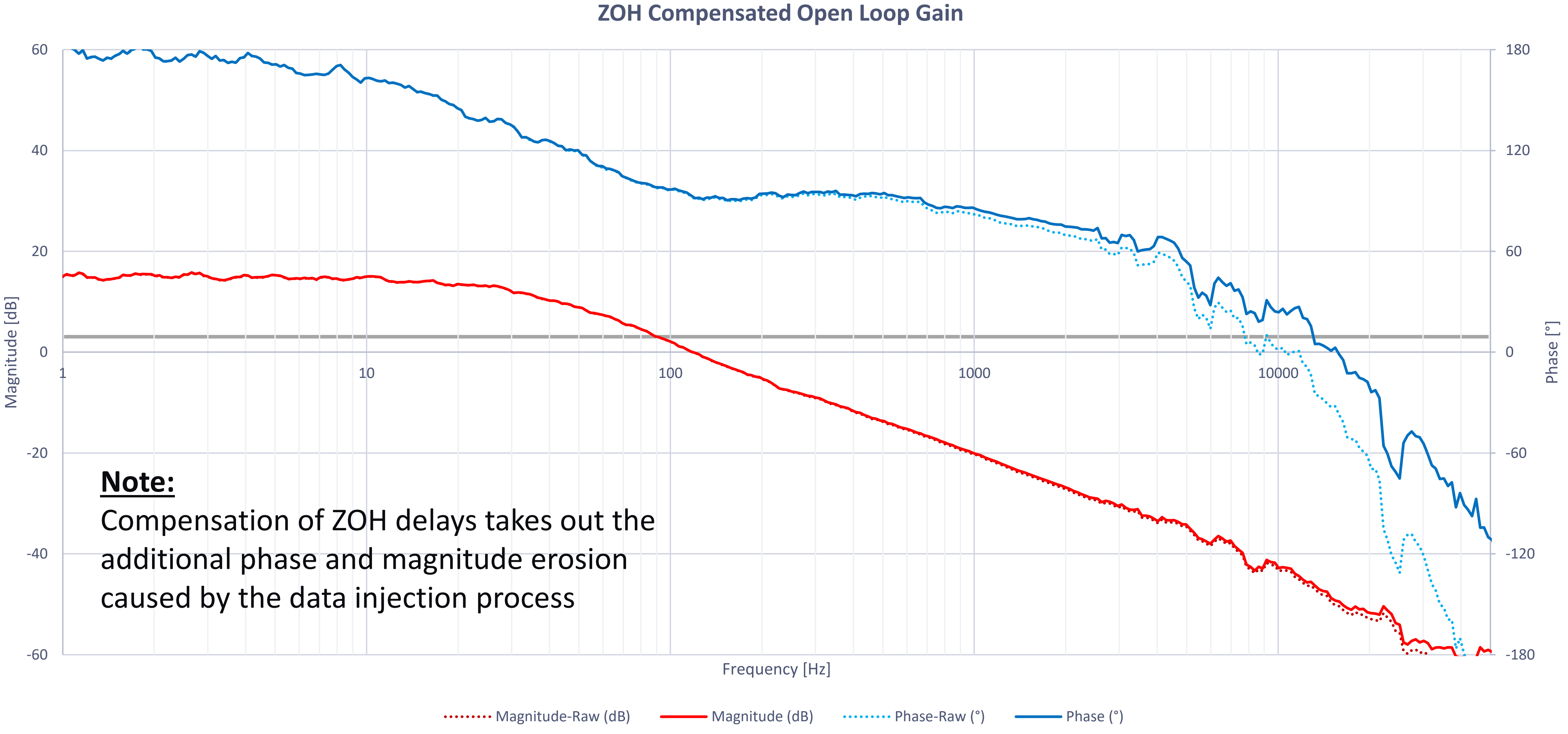
Zero Gain Calibration

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



Measurement Results 2.5 kW TTP PFC

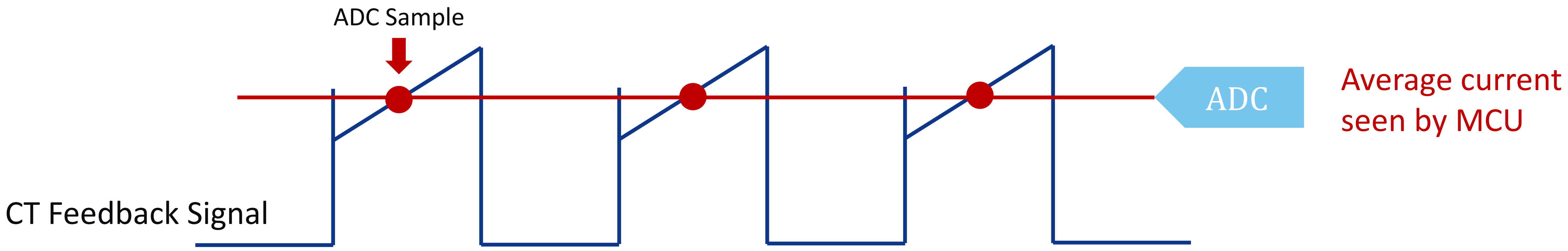


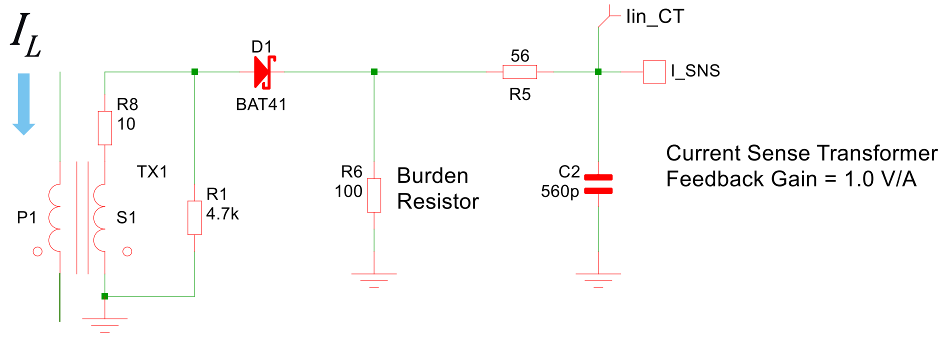
Note:

Compensation of ZOH delays takes out the additional phase and magnitude erosion caused by the data injection process

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

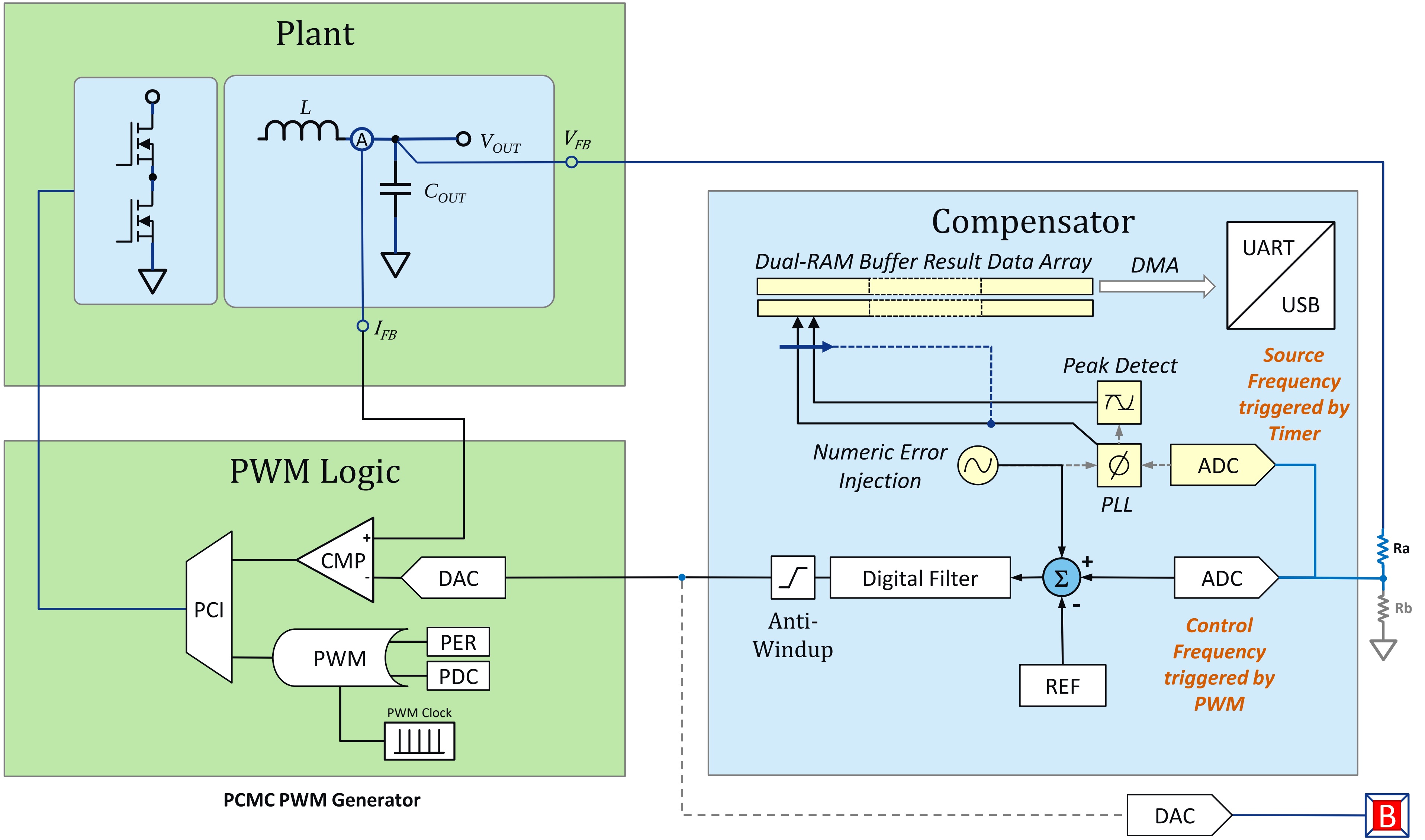
Additional Information

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

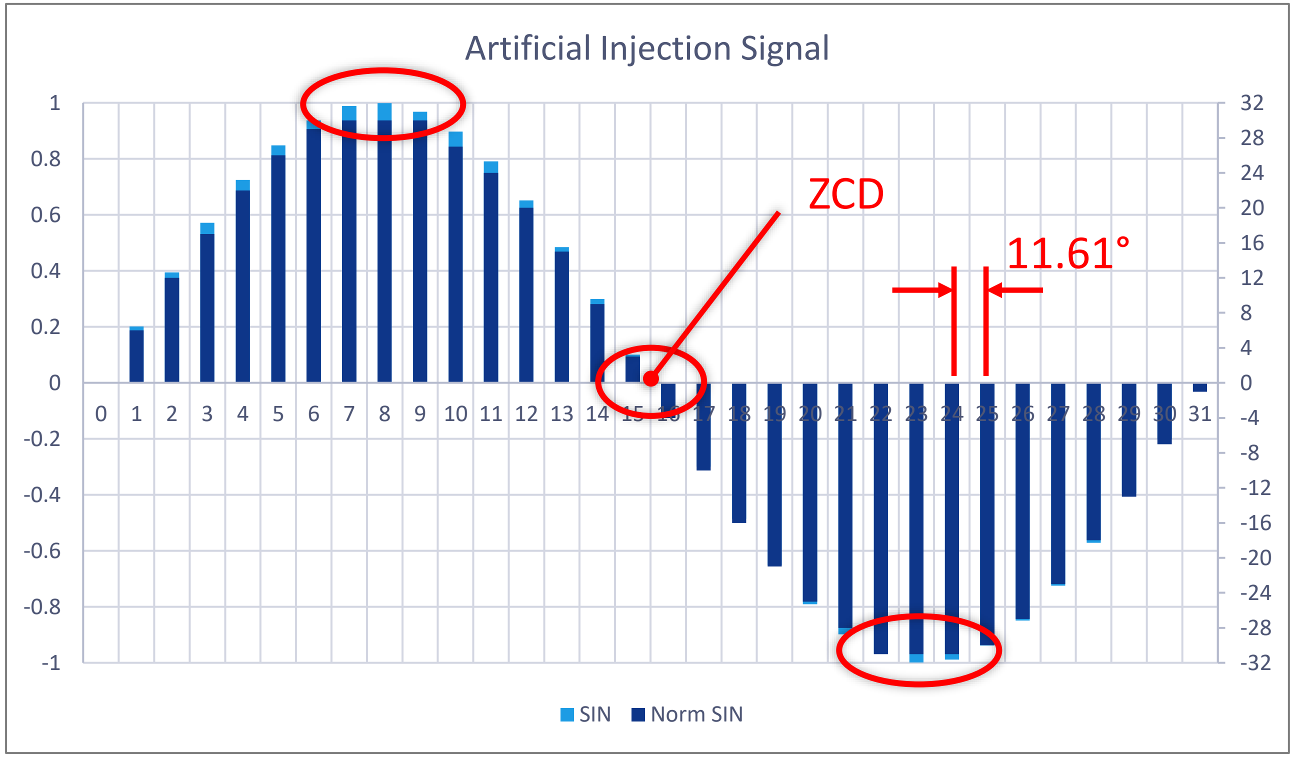
In-Chip Bode Measurement



PCMC PWM Generator

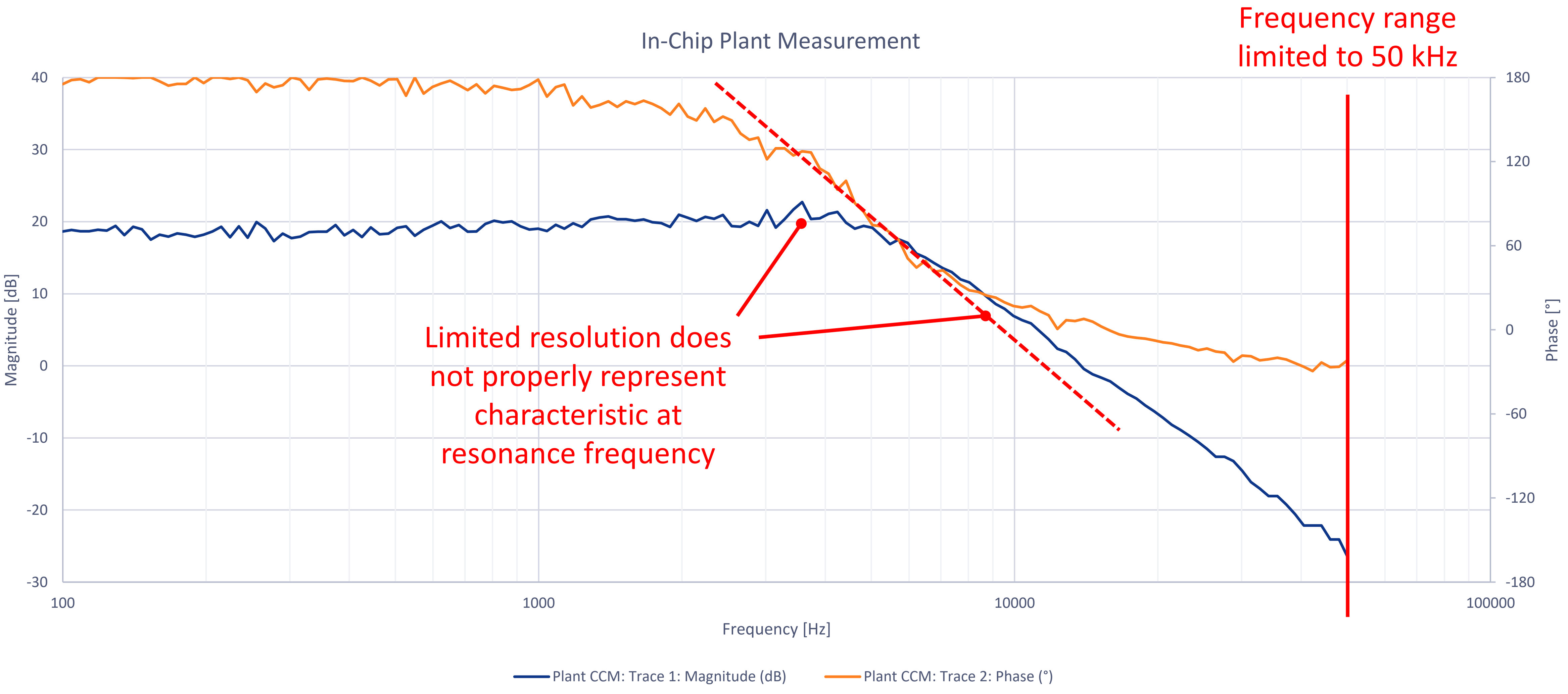
Digital PWM Controller Access Points

- **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] x [series size] = 50 kHz x 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

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UNIVERSITY

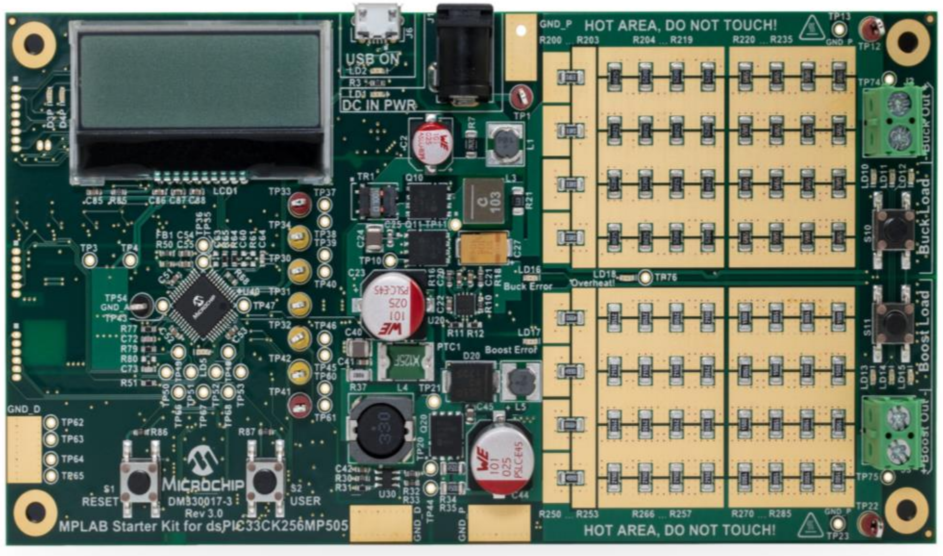
Please note:
All Face-2-Face workshops have been suspended in early 2020, including the well-known MASTERs conferences usually conducted in 9 nations around the globe. For the time being all available trainings have been moved to our new virtual training platform ***Microchip University***.

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

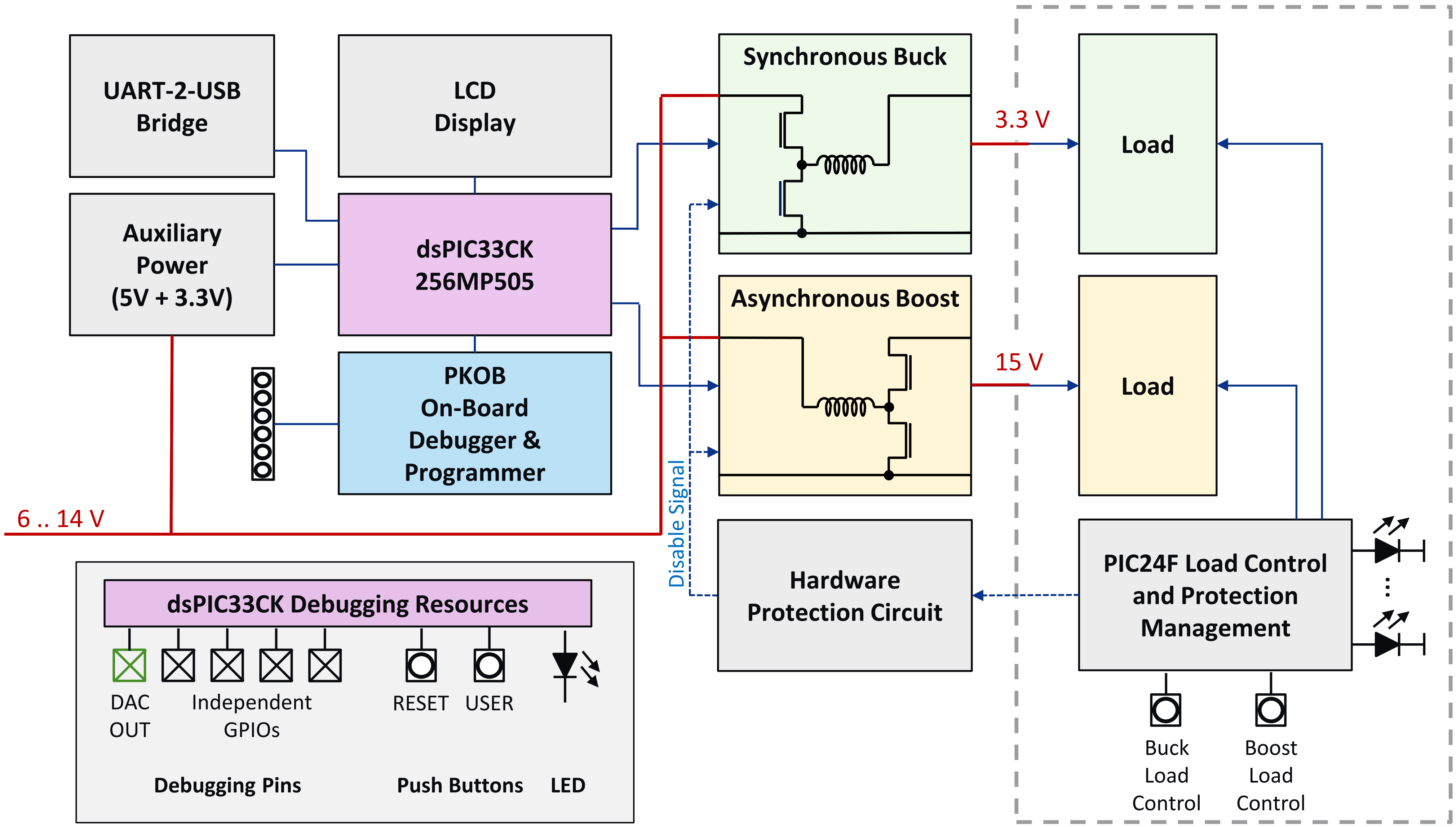


Available Now:

Order # DM330017-3

61

Digital Power Starter Kit 3 (DPSK3)



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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

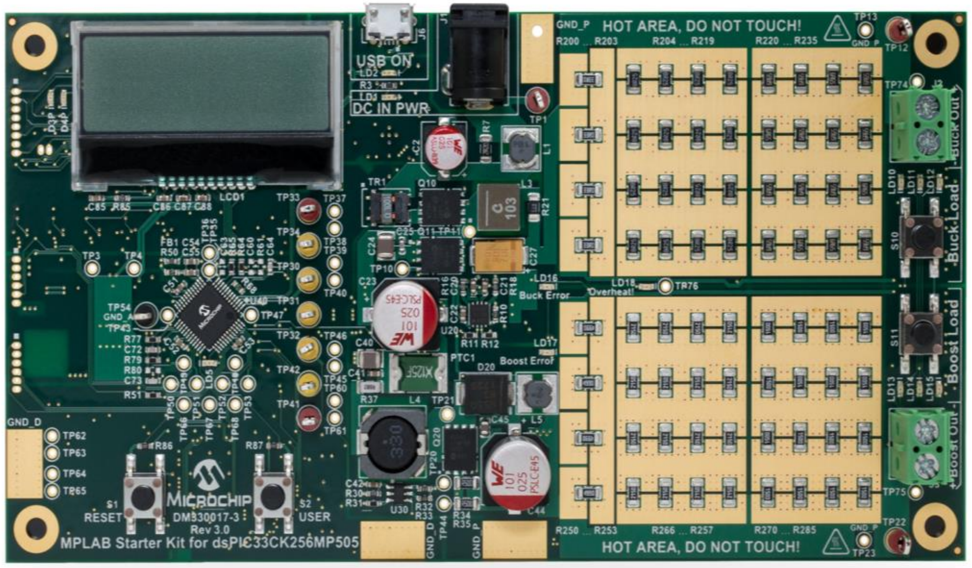
d) *Programming/Debugging*

- 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



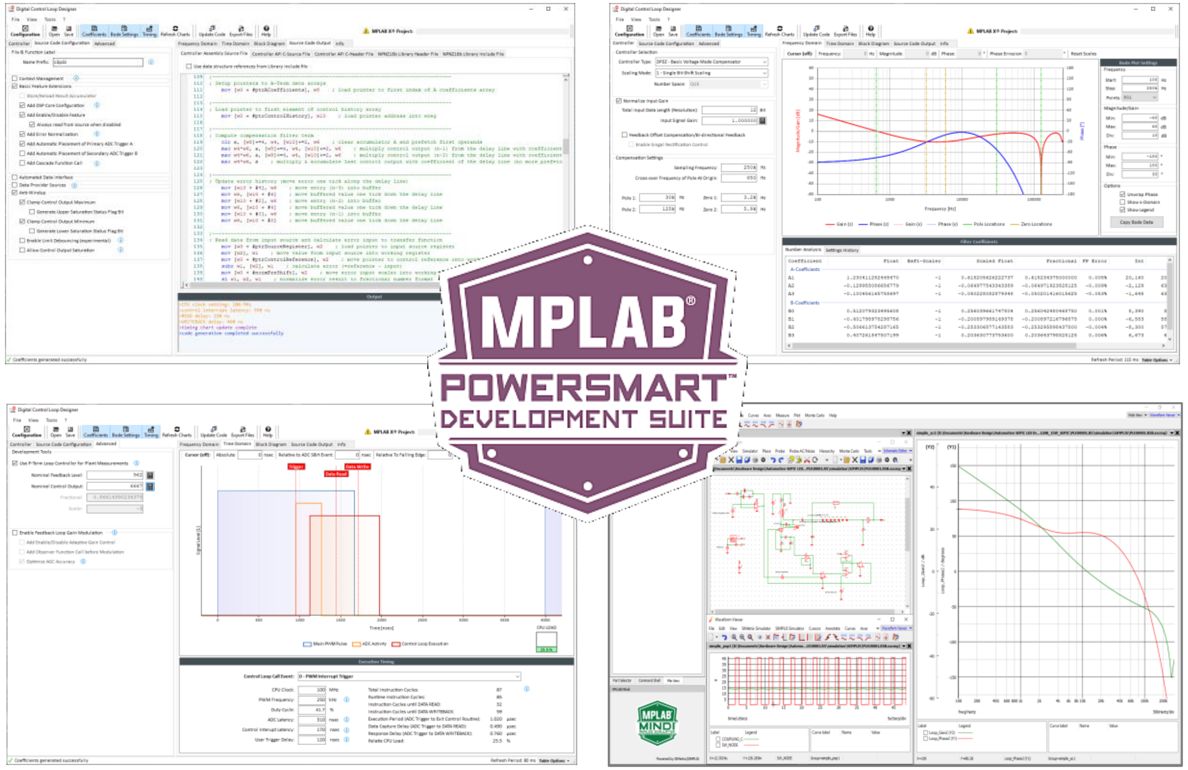
Available Now:
Order # DM330017-3

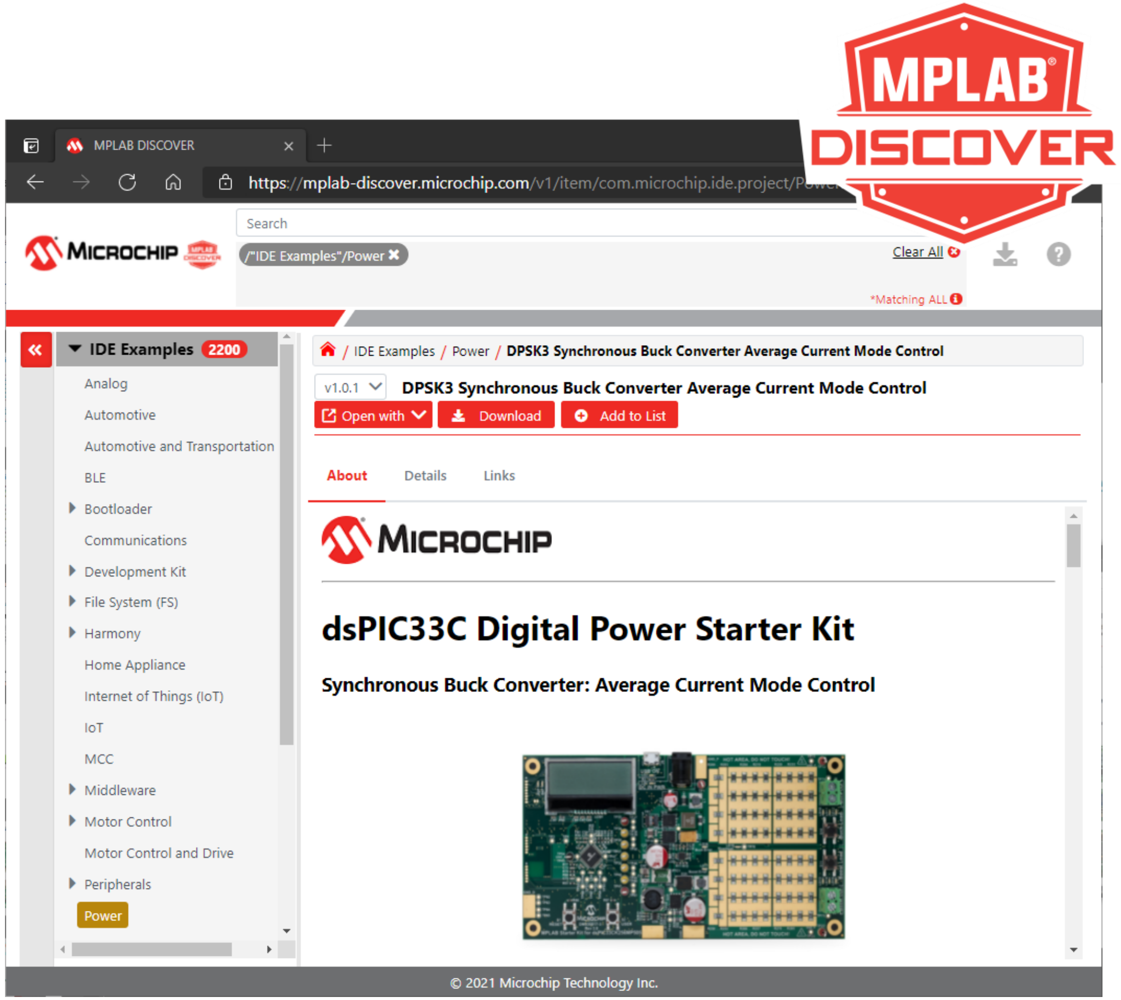
Available Code Examples

- **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