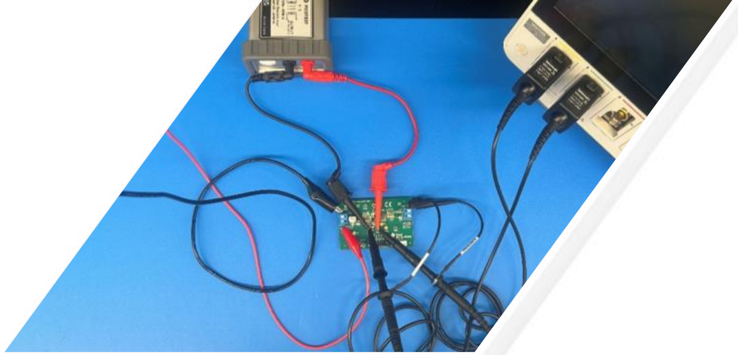
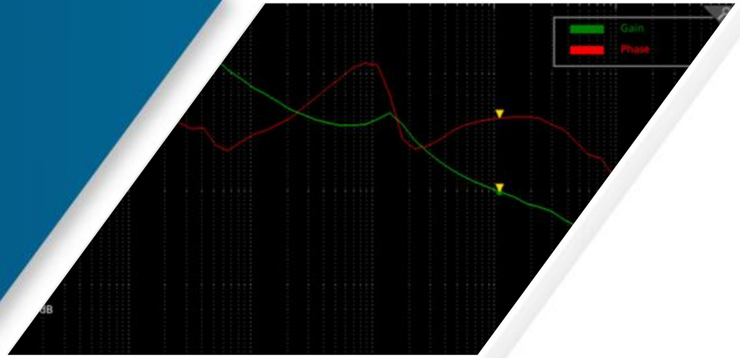
Sandia National Laboratories

Exceptional service in the national interest

METHOD TO OBTAIN BODE PLOT OF LIVE SWITCH MODE POWER CONVERTER COMPARING RESULTS WITH SIMULINK AND MATLAB SIMULATIONS





Kyle O. Rex (678) 237-2221 korex@sandia.gov (May 2026)

Texas A&M University Engineering Undergraduate R&D
Sandia National Laboratories Intern

Date: 08/07/2024
Manager: Paul Yoon
Mentor: Matthew McDonough
Organization: 08421

U.S. DEPARTMENT OF ENERGY NNSA National Nuclear Security Administration

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525

SAND2024-08533O

INTRODUCTION

PRESENTER INTRODUCTION

- Kyle Rex
- Mechatronics (Electrical, Mechanical, and Software) Engineering Undergraduate Program at Texas A&M University (May 2026) (ABET Accredited)
- 678-237-2221
- kyle.o.rex@tamu.edu & korex@sandia.gov
- Sandia National Laboratories Weapon Subsystems R&D Undergraduate Summer 2024 Intern

RESEARCH OBJECTIVE

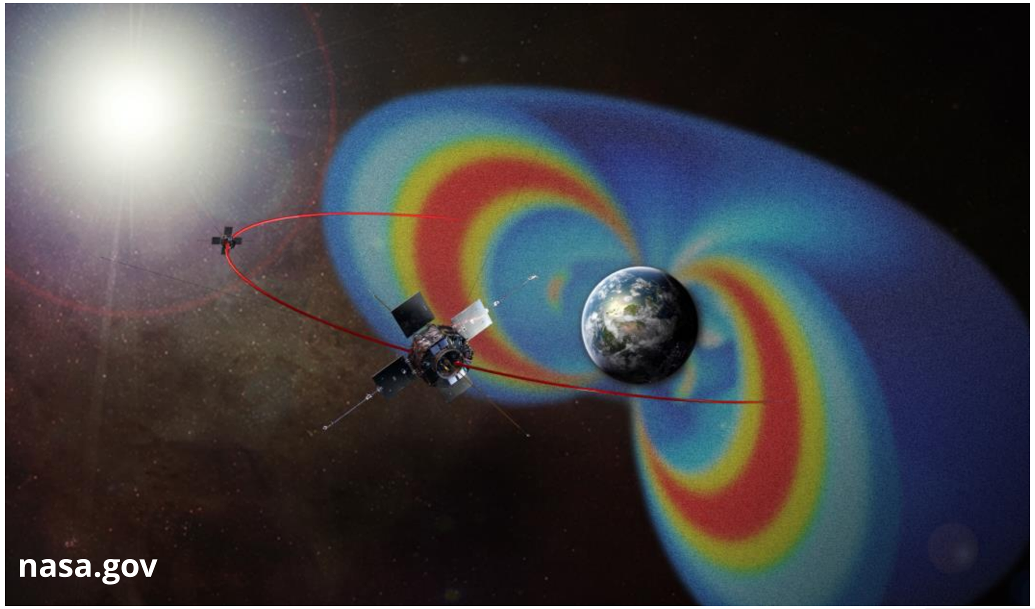
Create a toolchain to:

- Model a switched mode power converter and feedback controller
- Validate the closed loop controller performance with hardware measurements

BACKGROUND / SUPPORTING MISSION

- Broadening the understanding of Switch Mode Power Converters (SMPCs) and DC-to-DC feedback-controlled conversion, like a Buck Converter with a Type Three (III) Compensator system, the focus of this project, and its analysis is key to the future implementation and development of radiation hardened/resilient systems and technology for use in space missions and nuclear disaster response.

Fukushima Dai-ichi Reactor Incident

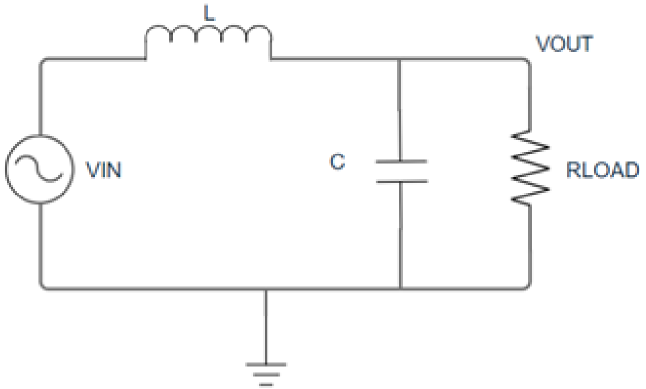


NASA Space Operations

BUCK CONVERTER & TYPE 3 COMPENSATOR OVERVIEW

TRANSFER FUNCTION BODE PLOTS USING MATLAB

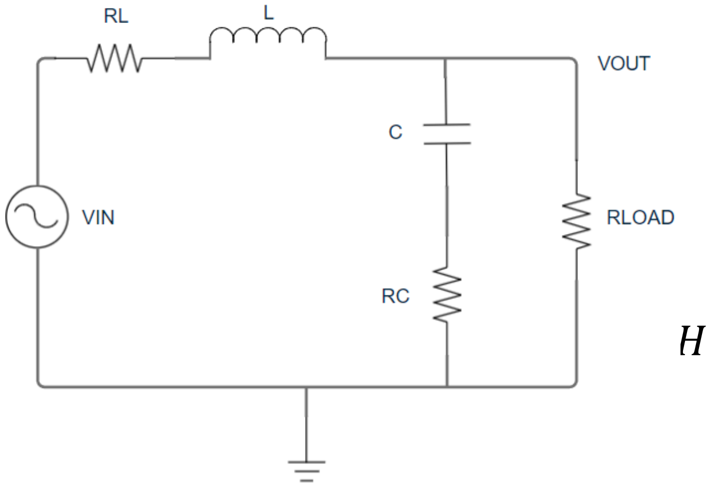
DC-TO-DC SWITCH MODE POWER BUCK CONVERTER (SMPC)



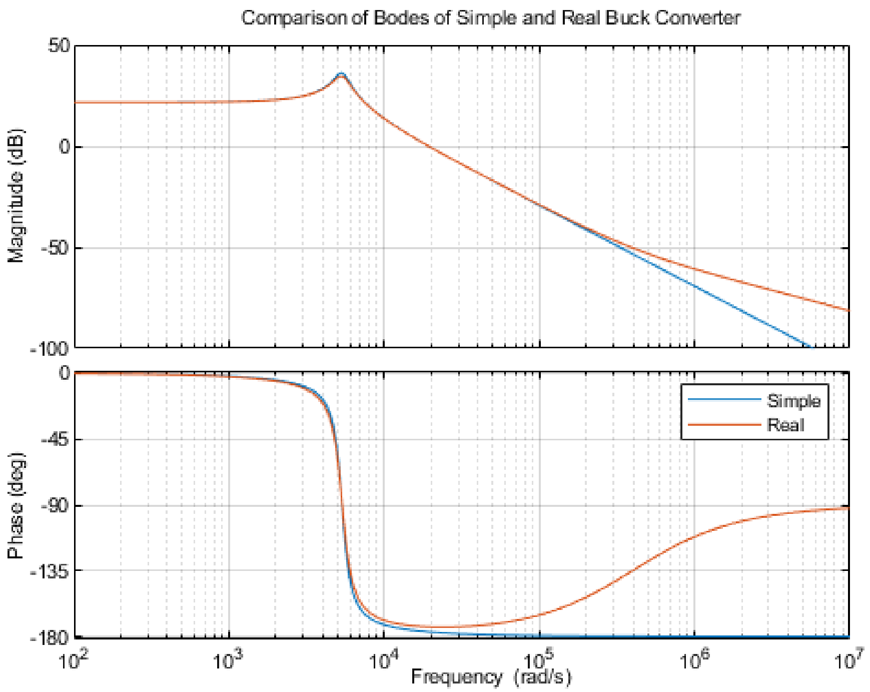
Simple LC Filter Buck Converter Circuit Diagram

$$H(s)_{SB} = \frac{V_{out}}{V_{in}} = \frac{R}{R + s * L + s^2 * R * L * C}$$

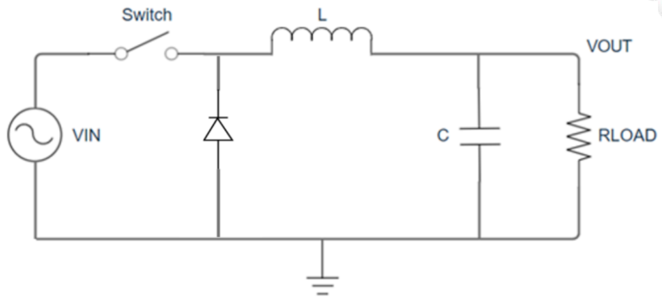
Simple LC Filter Buck Converter Transfer Function (SB)



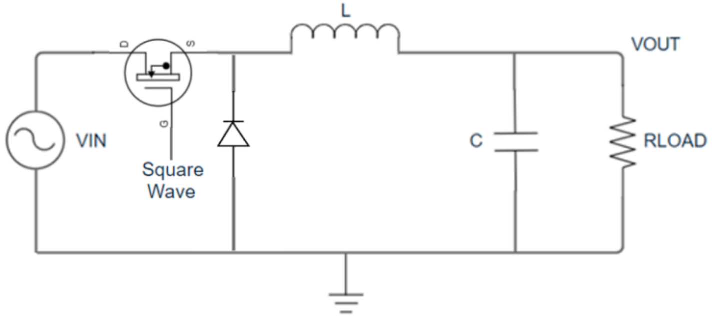
Real LC Filter Buck Converter Circuit Diagram – Parasitic Resistance



Comparison Bode Plot of Derived Simple DC-DC Buck Converter (Simple LC Filter) and Derived Real DC-DC Buck Converter (Real LC Filter)



Buck Converter with Switch Circuit Diagram

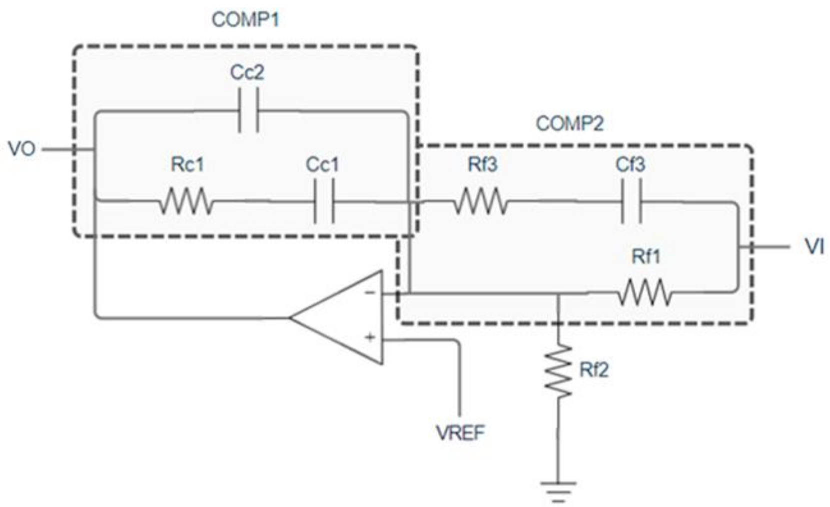


Buck Converter with MOSFET Circuit Diagram

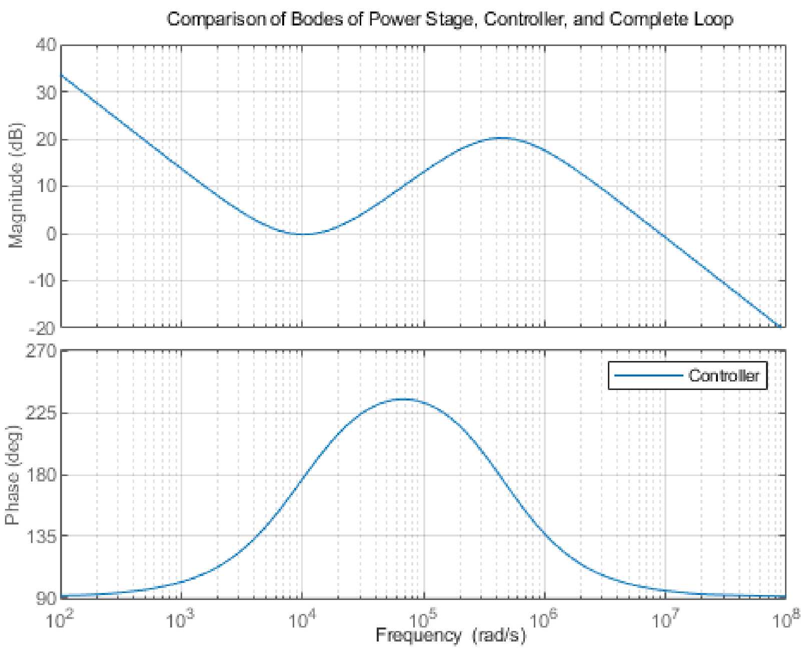
$$H(s)_{RB} = \frac{V_{out}}{V_{in}} = \frac{1 + (C * RC) * s}{1 + \frac{RL}{R} + \left(\frac{L}{R} + RC * C + RL * C + \frac{RL * RC * C}{R}\right) * s + \left(\frac{R + RC}{R}\right) * L * C * s^2}$$

Real LC Filter Buck Converter Transfer Function (RB)

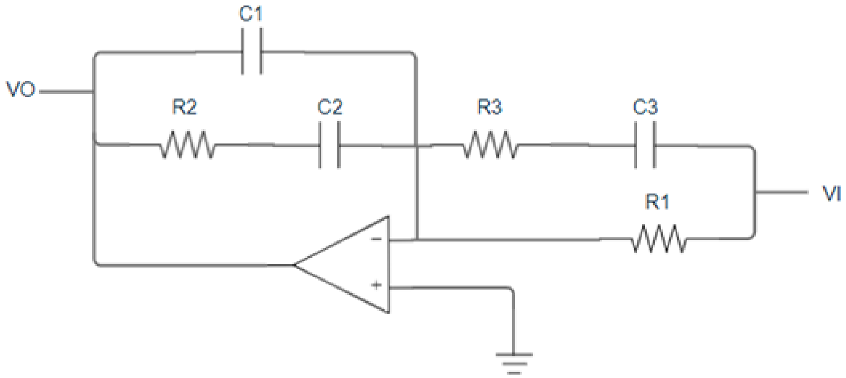
TYPE 3 COMPENSATOR FEEDBACK CONTROLLER



Type Three (III) Compensator + Circuit Diagram



Bode Plot of Derived Type III Compensator Controller



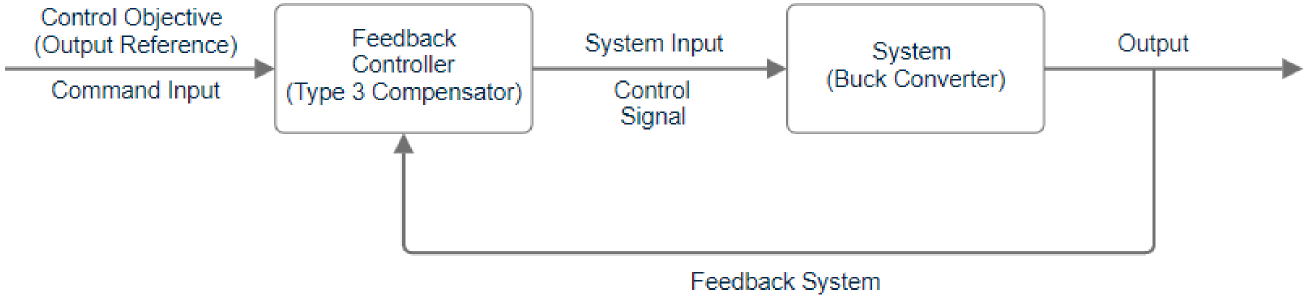
Type Three (III) Compensator Circuit Diagram

$$H(s)_{COMP} = \frac{V_{out}}{V_{in}} = -\frac{(s * C3 * (R1 + R3) + 1) * \ (s * C2 * R2 + 1)}{\left(s * R1 * (C1 + C2)\right) * \ (s * C3 * R3 + 1) * \ \left(s * \left(\frac{C1 * C2}{C1 + C2}\right) * R2 + 1\right)}$$

Type Three (III) Compensator Transfer Function

- The objective of this research is to create a method to obtain the bode plot of a live DC-to-DC feedback-controlled Buck (step-down) Converter with a Type Three (III) Compensator Switch Mode Power Converter (SMPC) with a Tektronix Mixed Signal Oscilloscope comparing its results with Simulink and MATLAB simulations for accuracy.

COMPLETE SYSTEM



Complete System Block Model

$$H(s)_{SYSTEM} = H(s)_{RB} * H(s)_{COMP} = H(s)_{RB} * H(s)_{COMP+}$$

Complete System Transfer Function

- $H(s)_{COMP+}$ represents the transfer function, that was made in MATLAB, with Reference Voltage, Voltage Divider, and Specific Op-Amp Implementations (Both transfer functions produced the same bode plot as shown below).

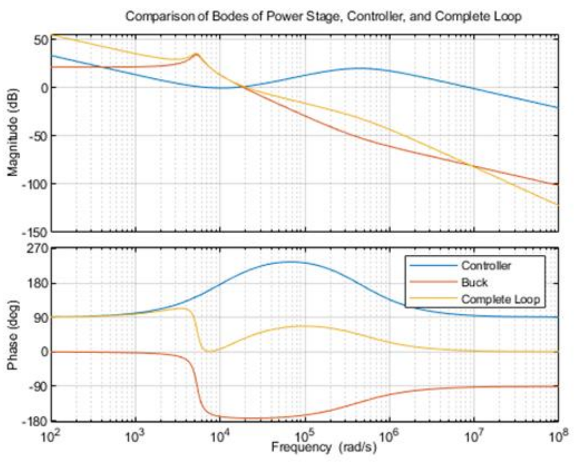
4 Comparison Bode Plots of Derived DC-DC Buck Converter with Derived Type III Compensator Controller with Voltage Divider and Specific Op-Amp Implementations

```
clc;
clear all;
close all;


%Identify Transfer Function Variable
s = tf('s');


% Buck Converter Values
R = 10;          % Load resistance (Ohm)
L = 350e-6;      % Inductor value (H)
C = 100e-6;      % Capacitor value (F)
RL = 0.050;      % Inductor resistance (Ohm)
RC = 0.025;      % Capacitor resistance (Ohm)
Vref= 1.2;       % Reference Voltage value (V)
Vout = 5;        % Output Voltage value (V)
Vin = 12;        % Input Voltage value (V)


% Transfer Function for Real Buck Converter
REALBUCKTOP = 1+(C*RC)*s;
REALBUCKBOTTOM = 1+(RL/R)+(L/R+RC*C+RL*C+(RL*RC*C)/R)*s+((R+RC)/R)*L*C*(s^2);
REALBUCKTF = Vin*(REALBUCKTOP/REALBUCKBOTTOM)


% Type III Compensator Controller Values
OpAmp=tf(1e6,1);              % Perfect OpAmp Configuration
Rf1 = 20e3;                   % Resistor Rf1 value (Ohm)
Rc1 = 12.4e3;                 % Resistor Rc2 value (Ohm)
Rf3 = 568;                    % Resistor Rf3 value (Ohm)
Cc2 = 200e-12;                % Capacitor Cc2 value (F)
Cc1 = 10.2e-9;                % Capacitor Cc1 value (F)
Cf3 = 3.7e-9;                 % Capacitor Cf3 value (F) (Control this to make
phase shift up and down)
Rf2=Rf1*Vref/(Vout-Vref);     % Voltage Divider Resistor Rf2 value (Ohm)


% Table of Type III Compensator Controller Values Displayed
compValues = [Rf1, Rf2, Rf3, Cc1, Cc2, Cf3, Rc1];
disp(table(Rf1, Rf2, Rf3, Cc1, Cc2, Cf3, Rc1))


% Derived Transfer Function for Type III Compensator Controller Accounting for
Voltage Divider and Specific Op-Amp
COMP1 = ((Rc1+1/(s*Cc1))*(1/(s*Cc2)))/((Rc1+1/(s*Cc1))+(1/(s*Cc2)));
```

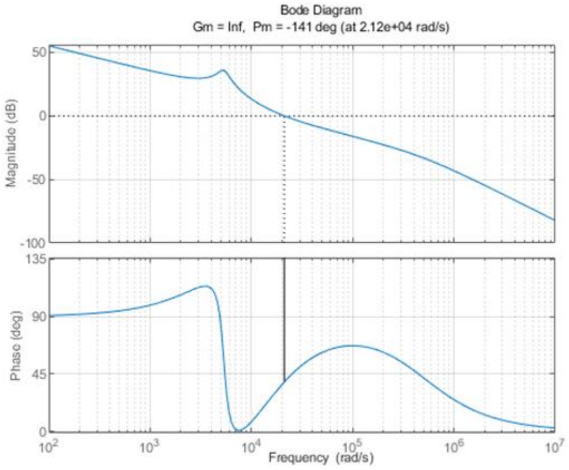
5 Comparison Bode Plots of Derived DC-DC Buck Converter with Derived Type III Compensator Controller

```
clc;
clear all;
close all;


%Identify Transfer Function Variable
s = tf('s');


% Buck Converter Values
R = 10;          % Load resistance (Ohm)
L = 350e-6;      % Inductor value (H)
C = 100e-6;      % Capacitor value (F)
RL = 0.050;      % Inductor resistance (Ohm)
RC = 0.025;      % Capacitor resistance (Ohm)
Vin = 12;        % Input Voltage value (V)


% Transfer Function for Real Buck Converter
REALBUCKTOP = 1+(C*RC)*s;
REALBUCKBOTTOM = 1+(RL/R)+(L/R+RC*C+RL*C+(RL*RC*C)/R)*s+((R+RC)/R)*L*C*(s^2);
REALBUCKTF = Vin*(REALBUCKTOP/REALBUCKBOTTOM)


% Type III Compensator Controller Values
R1 = 20e3;       % Resistor R1 value (Ohm)
R2 = 12.4e3;     % Resistor R2 value (Ohm)
R3 = 568;        % Resistor R3 value (Ohm)
C1 = 200e-12;    % Capacitor C1 value (F)
C2 = 10.2e-9;    % Capacitor C2 value (F)
C3 = 3.7e-9;     % Capacitor C3 value (F) (Control this to make phase shift up and
down) (Ex:30.4e-9)


% Table of Type III Compensator Controller Values Displayed
compValues = [R1, R2, R3, C1, C2, C3];
disp(table(R1, R2, R3, C1, C2, C3))


% Derived Transfer Function for Type III Compensator Controller
COMPTOP =(s*C3*(R1+R3)+1) * (s*C2*R2+1);
COMPBOTTOM =(s*R1*(C1+C2)) * (s*C3*R3+1) * (s*((C1*C2)/(C1+C2))*R2+1);
COMPLETECOMP = (-1)*COMPTOP/COMPBOTTOM


% Comparison Bode Plot Displayed
```

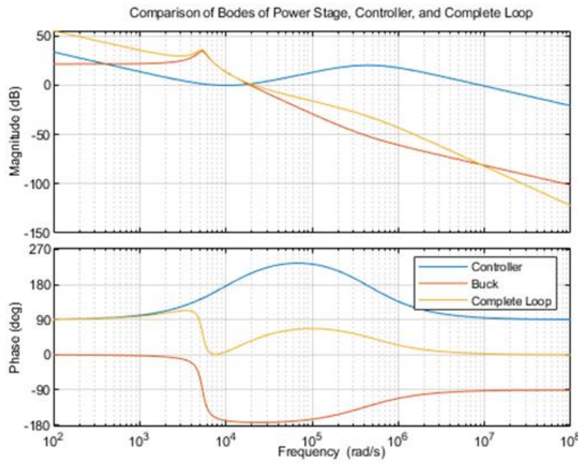
Snippets of MATLAB Code Sequences



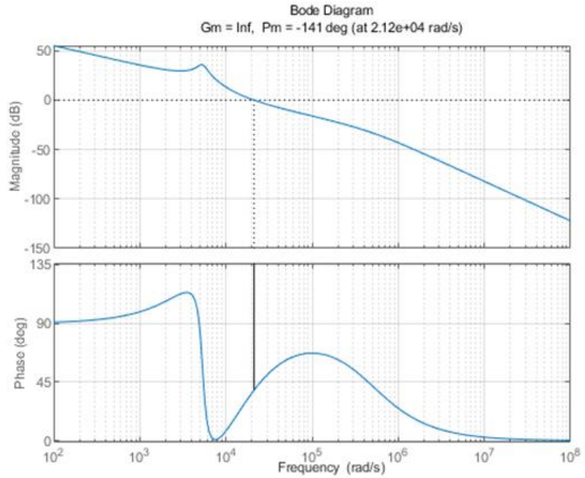
Comparison Bode Plot of Derived DC-DC Buck Converter with Derived Type III Compensator Controller



Margin Bode Plot of Derived DC-DC Buck Converter with Derived Type III Compensator Controller



Comparison Bode Plot of Derived DC-DC Buck Converter with Derived Type III Compensator Controller with Voltage Divider and Specific Op-Amp Implementations

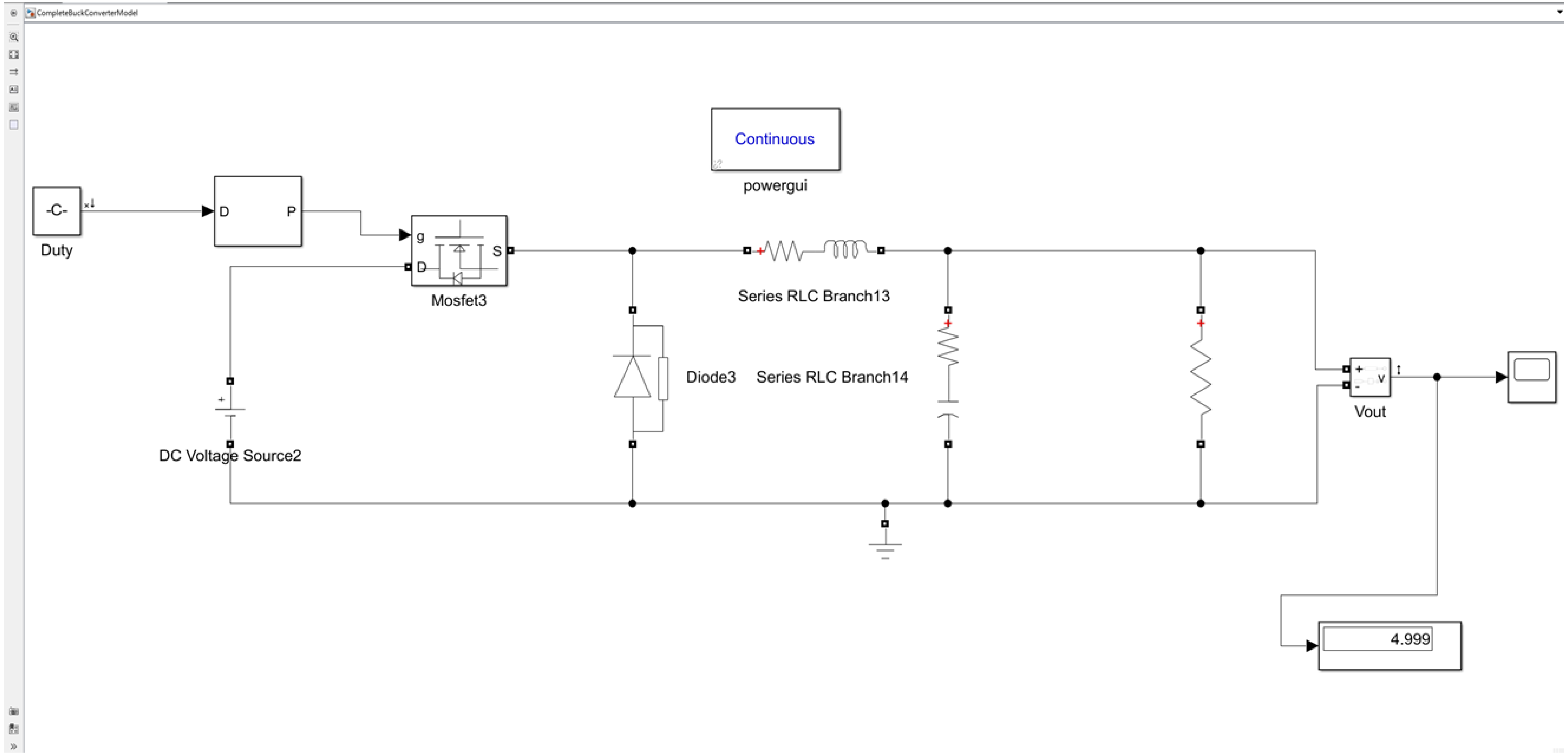


Margin Bode Plot of Derived DC-DC Buck Converter with Derived Type III Compensator Controller with Voltage Divider and Specific Op-Amp Implementations

SIMULATION BODE PLOTS USING SIMULINK

COMPARING BODE PLOTS

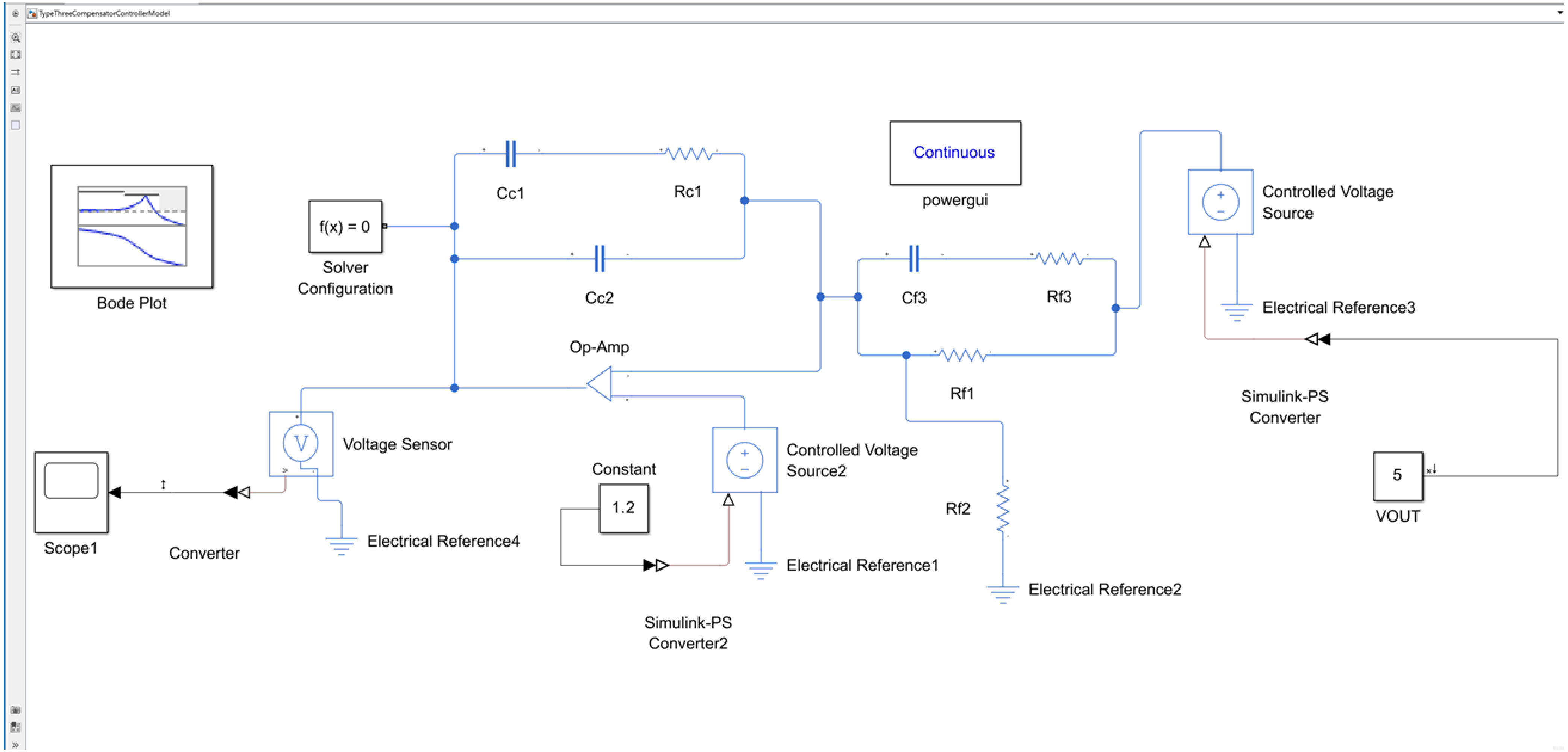
BUCK CONVERTER MODEL



Model Simulink Simulation DC-DC Buck Converter

- Creating bode plots from model simulations began by creating the models in Simulink and configuring them with appropriate components and values to operate correctly.

TYPE 3 COMPENSATOR FEEDBACK CONTROLLER MODEL



Model Simulink Simulation Type III Compensator Controller

- With the working simulations the next step was to change the values to match the values used in the previous derived transfer function testing.

COMPLETE SYSTEM

```
% 7
% Code to Estimate Transfer Function of Model Simulink Simulation of Buck Converter
% Save result from workspace as BuckModelTransferFunction.mat file to use in
BuckConverterFeedbackController Design
% This code will take a few minutes to run
% Code will produce Bode Plot and other figures to see

function transferFunc = EstimateTransferFunctionFromBuckModel()
mdl = 'CompleteBuckConverterModel';
open_system(mdl);
ios = [linio([mdl,'/Duty'],1,'input'); linio([mdl,'/Vout'],1,'output')];
f = logspace(log10(200),log10(20000),100);
in = frest.Sinestream('Frequency',f,'Amplitude',0.03);
getSimulationTime(in)/0.02
[sysData,simlog] = frestimate(mdl,ios,in);
bopt              = bodeoptions;
bopt.Grid         = 'on';
bopt.PhaseMatching = 'on';
figure, bode(sysData,'*r',bopt)
frest.simView(simlog,in,sysData);
sysA = tfest(sysData,4)
figure, bode(sysData,'r*',sysA,bopt)
num = sysA.Numerator
den = sysA.Denominator
sys = tf(num,den)
transferFunc = sys
figure, rlocus(sys)
end
```

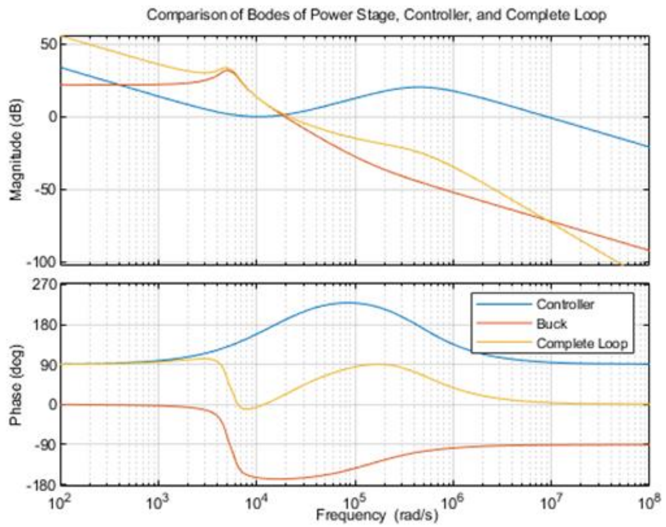
Snippet of MATLAB Code Sequence

- With the working and configured simulations, the next step was to find a way to get a transfer function to represent the simulation that could be used in MATLAB to create bode plots using the specialized MATLAB functions.

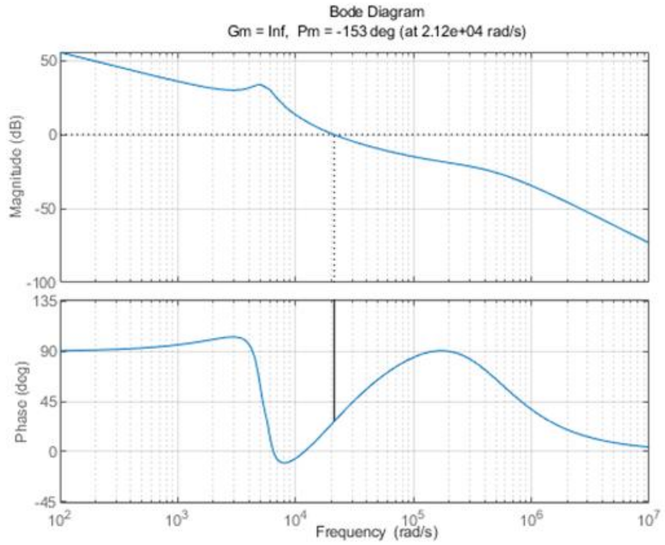
1 Comparison Bode Plots of Model Simulink Simulation DC-DC Buck Converter with Model Simulink Simulation Type III Compensator Controller

```
clc;
clear all;
close all;


%Identify Transfer Function Variable
s = tf('s');


% Assign Estimated Transfer Function From Buck Model Simulink Simulation
REALBUCKTF = load("BuckModelTransferFunction.mat").ans


% Buck Converter Model Simulink Simulation Values for Reference
%Vin = 12;       % Input Voltage value (V)
%Vout = 5;       % Output Voltage value (V)
%R = 10;         % Load resistance (Ohm)
%L = 350e-6;     % Inductor value (H)
%C = 100e-6;     % Capacitor value (F)
%RL = 0.050;     % Inductor resistance (Ohm)
%RC = 0.025;     % Capacitor resistance (Ohm)
%D = 0.4569;     % Duty Cycle Constant
%PWM = 250e3;    % PWM Generator Switching Frequency (Hz)


% Assign Estimated Transfer Function From Comp Model Simulink Simulation
COMPLETECOMP= load("TypeThreeCompensatorController.mat").ans


% Type III Compensator Controller Model Simulink Simulation Values for Reference
%Vref= 1.2;                  % Reference Voltage value (V)
%Vout = 5;                   % Output Voltage value (V)
%Rf1 = 20e3;                 % Resistor Rf1 value (Ohm)
%Rc1 = 12.4e3;               % Resistor Rc2 value (Ohm)
%Rf3 = 568;                  % Resistor Rf3 value (Ohm)
%Cc2 = 200e-12;              % Capacitor Cc2 value (F)
%Cc1 = 10.2e-9;              % Capacitor Cc1 value (F)
%Cf3 = 3.7e-9;               % Capacitor Cf3 value (F) (Control this to make
phase shift up and down)
%Rf2= 6315.8;                % Voltage Divider Resistor Rf2 value (Ohm)


% Comparison Bode Plot Displayed
figure()
options = bodeoptions;
options.FreqUnits = 'rad/s';
```

Snippet of MATLAB Code Sequence



Comparison Bode Plot of Model Simulink Simulation DC-DC Buck Converter with Model Simulink Simulation Type III Compensator Controller



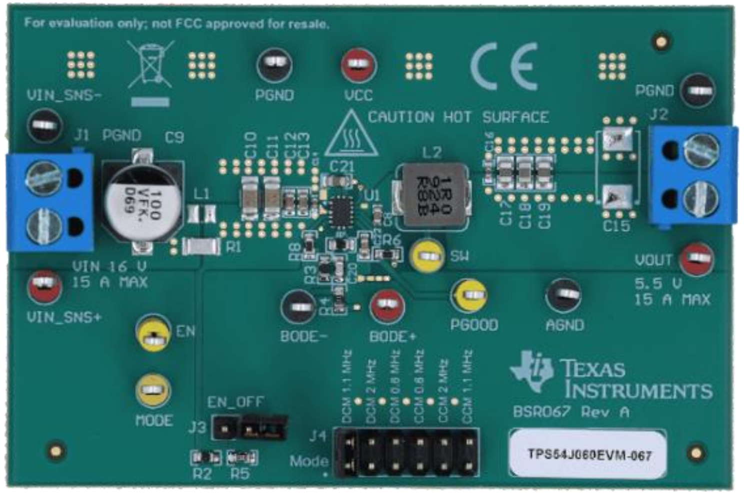
Margin Bode Plot of Model Simulink Simulation DC-DC Buck Converter with Model Simulink Simulation Type III Compensator Controller

BODE PLOTS FROM HARDWARE

HARDWARE TOOLSET & TEST PROCEDURE

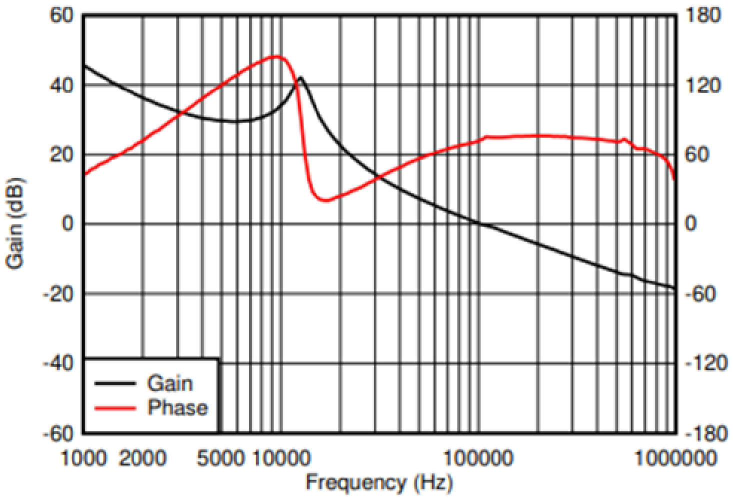
Key: * = Image from Texas Instruments

TEST CIRCUIT SELECTION



TPS54J060EVM-067 Circuit Top View*

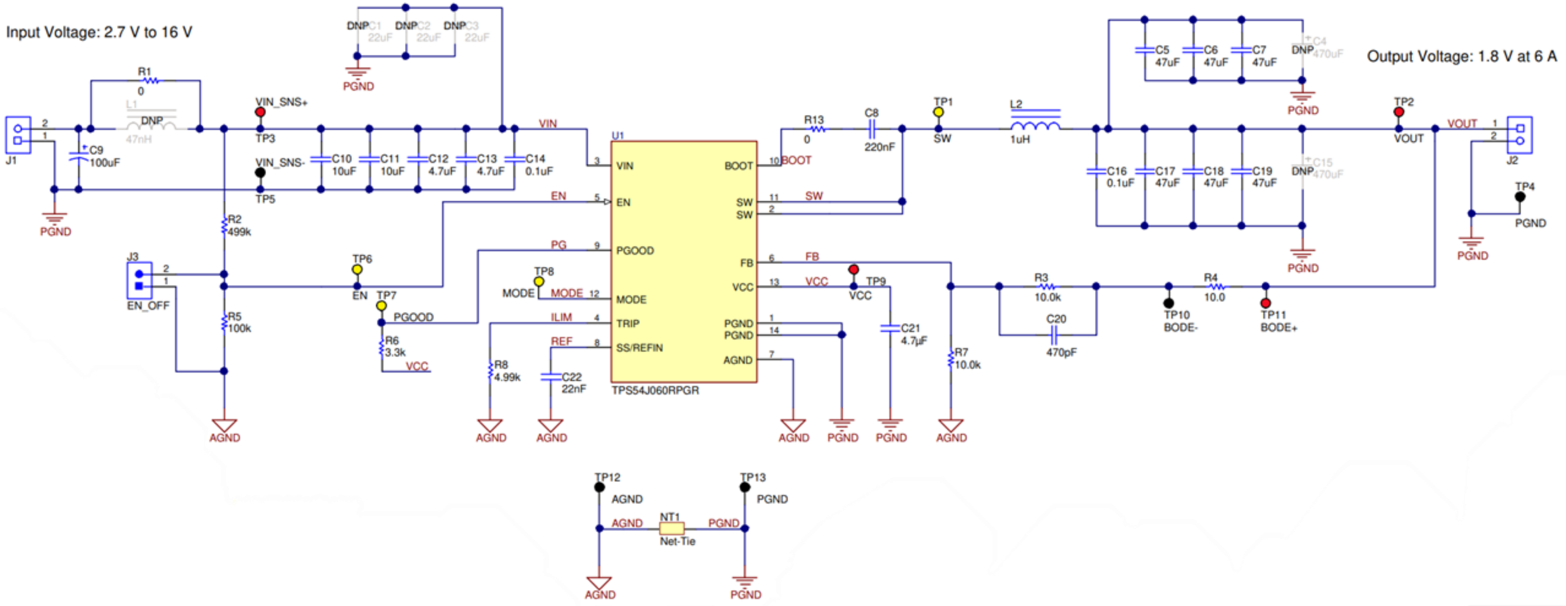
- The circuit that was selected had to meet certain requirements including having a Buck Converter topology (so it matches previous simulations), having a schematic (so it can be properly simulated), and having access to bode input/output points that are not buried inside the board.



TPS54J060EVM-067 Ideal Bode Plot*

- Texas Instruments Analog Evaluation Module for the TPS54J060 (TPS54J060EVM-067)

TPS54J060EVM-067 Circuit Side View*

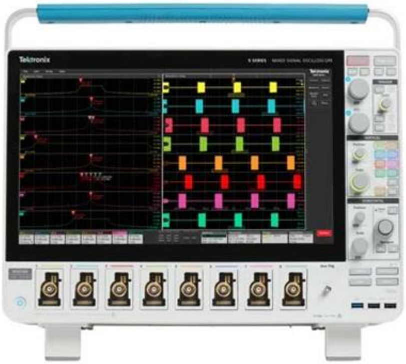


TPS54J060EVM-067 Circuit Schematic*

TEST HARDWARE TOOLSET

Hardware Toolset

System or Part	Quantity
Tektronix 5 Series Mixed Signal Oscilloscope (MSO58B) (2 GHz) * (Or other appropriate Tektronix Mixed Signal Oscilloscope) *Must have SUP5-PWR and SUP5-AFG licenses.	1
Picotest 10 Hz - 45 MHz Injection Transformer (J2101A) (Or other appropriate Injection Transformer)	1
Texas Instruments Analog Evaluation Module for the TPS54J060 (TPS54J060EVM-067) (Or other DC-to-DC Feedback-Controlled Converter that fits requirements)	1
Tektronix TPP1000 1 GHz Passive Voltage Probe (Or other appropriate Voltage Probe)	2
Keysight Triple Output Programmable DC Power Supply (E36313A) (Or other appropriate DC Power Supply)	1
Banana to Grabber Voltage Plugs (Or other appropriate cord setup)	1
Banana to Gator Voltage Plugs (Or other appropriate cord setup)	1
BNC to BNC Cable (Or other appropriate cord setup)	1



Tektronix 5 Series Mixed Signal Oscilloscope (MSO58B)**

Keysight Triple Output Programmable DC Power Supply (E36313A)***

Tektronix TPP1000 1 GHz Passive Voltage Probe**

Picotest J2101A 10 Hz - 45M Hz Injection Transformer****

BNC to BNC Cable*

Banana to Gator Voltage Plugs*

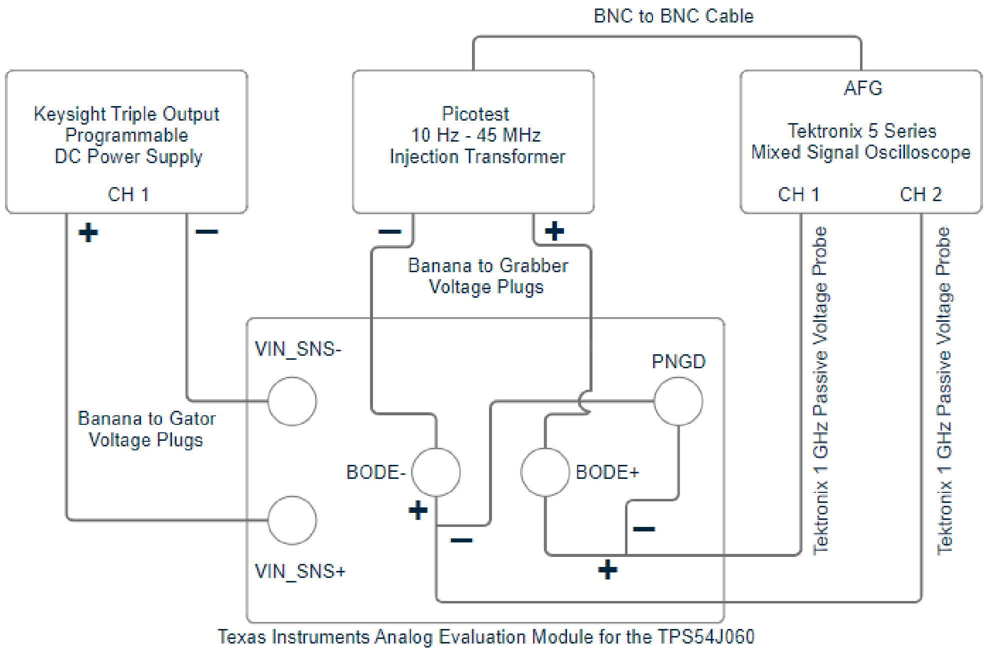
Banana to Grabber Voltage Plugs*

Key: * = Image from DigiKey, ** = Image from Tektronix, * = Image from Keysight, **** = Image from Picotest**

TEST SETUP, PROCEDURE, AND EXECUTION

Test Information Summary

Program Name: Bode Plot	**Test Item:** TI Analog Eval Module for TPS54J060	**Test Plan (TK):** Test Plan is in sub-section 4.3.5
Test Location: George H. W. Bush Combat Development Complex 717 RELLIS Parkway Bryan, TX 77807	**Test Start:** Time: 1030 Date: 06/21/2024	**Test End:** Time: 1045 Date: 06/21/2024
Program Lead: Matthew McDonough	**Test Lead:** Kyle Rex	



Test System Configuration for TPS54J060EVM-067

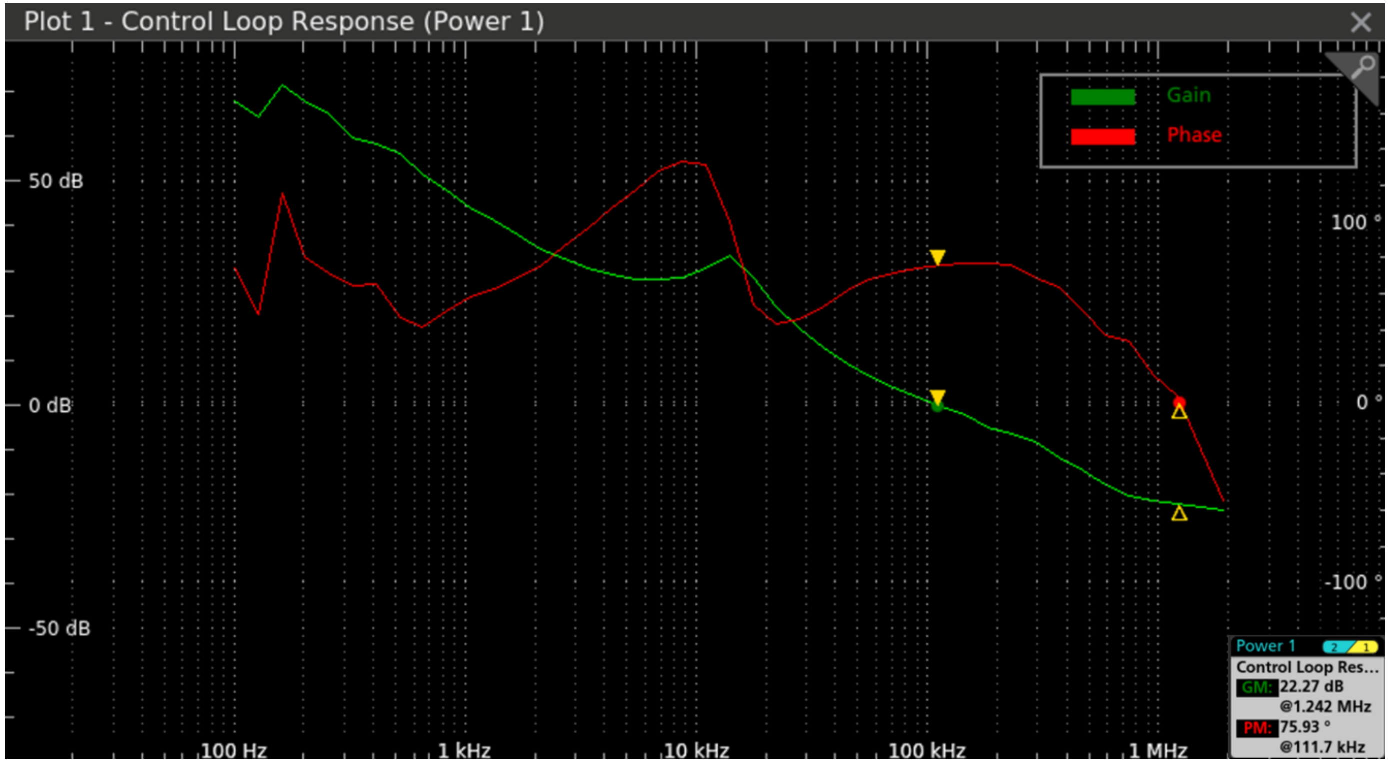
TEST SETUP (shown in the top right)

- Identify voltage input points, ground reference, and bode injection points of the DC-to-DC converter
- Connect AFG to the Injection Transformer
- Connect Injection Transformer to bode injection points
- Connect Oscilloscope Channels to bode injection points and ground
- Connect the DC Power Supply to the voltage input points

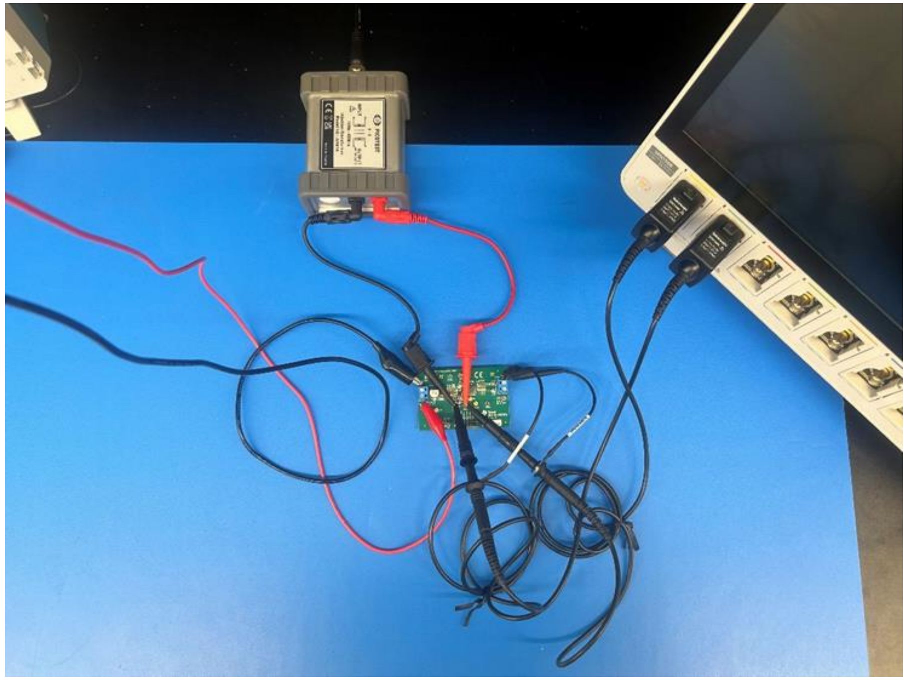
TEST PROCEDURE

- Setup test and configure all testing systems and tools appropriately
- Set DC power supply to apply required input voltage
- Access the control loop response measurement from the frequency response analysis tool kit on the oscilloscope
- Configure the measurement menu and assign the input and output being measured
- Setup and configure the Power and Control Loop Response menus by identifying all test constraints
- Run the test by enabling the internal function generator
- Analyze resulting bode plot for accuracy

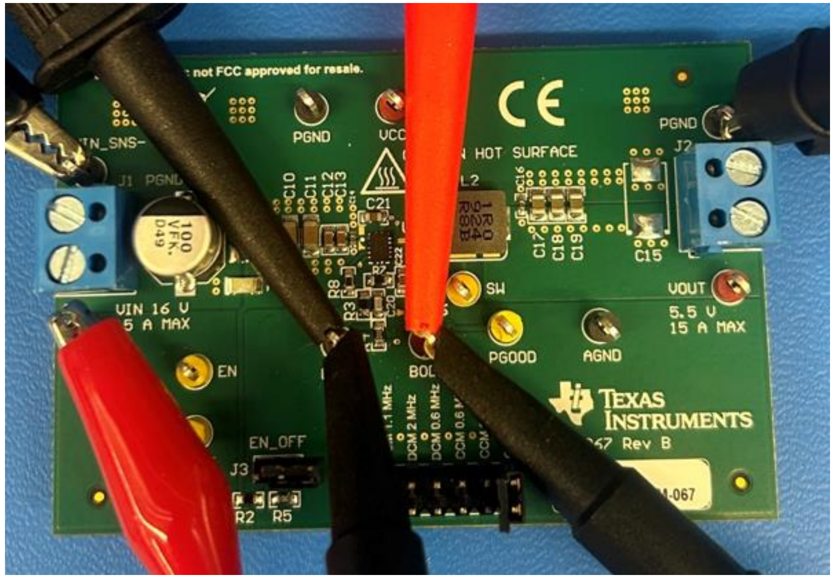
TEST RESULTS SUMMARY



Test Result Bode Plot for TPS54J060EVM-067



Close View of Real Test System Configuration for TPS54J060EVM-067



Focused View of Real Test System Configuration for TPS54J060EVM-067

- The results of the test confirmed that the hardware tool set and test procedure will produce the correct bode plot of a DC-to-DC converter.

CONCLUSION

REGRETS, NEXT STEPS, & CURRENT WORK

- Regrets
  - Was unable to create a Simulink model and create bode plot results for the actual TI Analog Eval Module schematic being tested
- Next Steps
  - Create more accurate MATLAB and Simulink simulation results by better modeling the TI board feedback system in Simulink
- Current Work
  - Using Altium to design actual Feedback Controller on test board for practical analysis