Qspice - Bode Frequency Response Analysis (.bode)

KSKelvin Kelvin Leung
11-8-2023

Qspice - Bode Frequency Response Analysis (.bode)

- Frequency Response Analysis (.bode)
  - Suggest to firstly read the help file in Qspice
    HELP > Simulator > Command Reference > Frequency Response Analysis (.bode)
  - A series perturbing voltage source must be inserted in input (open loop) or feedback (close loop)
  - Both terminal of this perturbing voltage source must not be grounded
  - **Syntax: .bode <SOURCE> <TSETTLE> [<FSTART> [<FSTOP> [<AMP>]]]**
    - .bode is time domain analysis with perturbing voltage source <SOURCE> generates signal from frequency <FSTART> to <FSTOP> with fixed or variable [.options Bodeampfreq / BodeLoPow / BodeHiPow] amplitude <AMP>. Time domain data must collect after circuit settle to steady state <TSETTLE>
    - Simulator performs frequency/phase analysis/deconvolution between output node [.options BODEOUT] and input node [.options BODEIN], and store results into *OpenLoopGain* or *TransferFunction*

Syntax

Name	Description	Default
SOURCE[2]	Name of the perturbing voltage source inserted in the loop	No default but a value is required
TSETTLE[3]	Time required for the circuit to settle to steady state	No default but a value is required
FSTART[4]	Lowest frequency to analyze	1kHz
FSTOP	Highest frequency to analyze	1000 × FSTART
AMP[5]	Minimum amplitude of perturbing source	2mV

.option

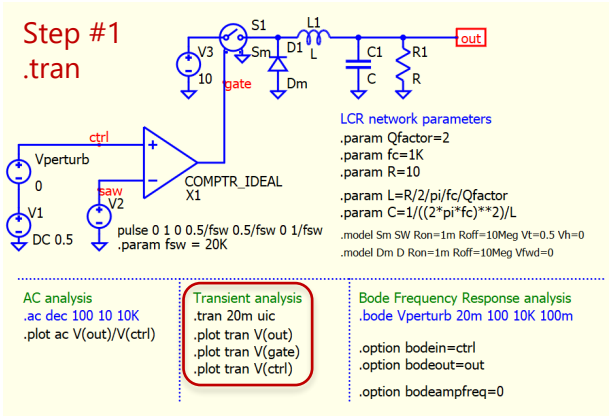
Name	Description	Default
BODEAMPFREQ	Frequency with the minimum perturbation amplitude. Set to 0. for constant amplitude.	(not set)
BODEHIPOW	Controls perturbation amplitude for above BODEAMPFREQ by pow (freq/BODEAMPFREQ, BODEHIPOW)	1.
BODEINPUT[1]	Override input node for transfer function computation(AKA BODEIN)	auto
BODELOPOW	Controls perturbation amplitude for below BODEAMPFREQ by pow (freq/BODEAMPFREQ, BODELOPOW)	1.
BODEPERIODS	Maximum number of periods to include in deconvolution	20
BODEREF	Reference node to use for Frequency Response Analysis	Node 0 (global ground)
BODEOUTPUT[1]	Override output node for transfer function computation(AKA BODEOUT)	auto
BODETOL	A Frequency Response Analysis relative tolerance	10.

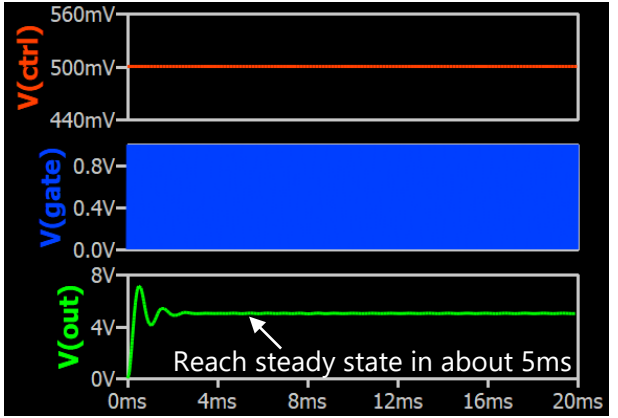
Basic Workflow of using .bode

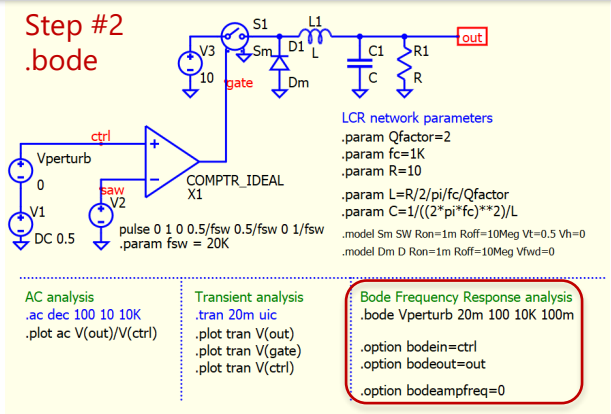
Qspice : Bode - Buck - transfer function.qsch

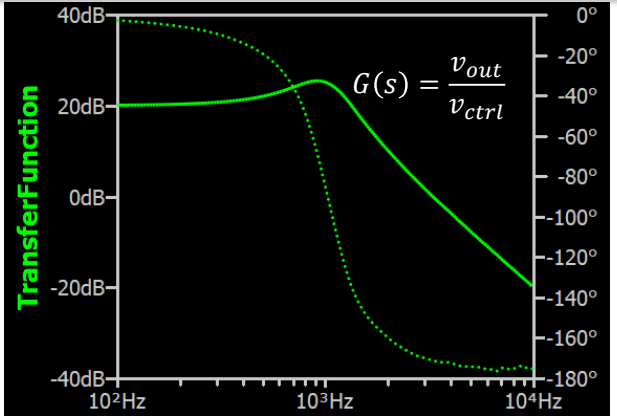
- Identify <Tsettle> with .tran
  - [1] Use .tran to identify settling time for system to reach steady state

- Setup .bode with
  - [2] Add perturbing source to a suitable position
    - both terminals must not be grounded
  - [3] Set <Tsettle> larger than steady state time found in [1]
  - [4] User determine <Fstart> and <Fstop>
    - Within 3 decade and prevent <Fstart> from very low frequency to reduce simulation time
  - [5] Determine Transfer Function by specifying
    - .option bodein=<input node>
    - .option bodeout=<output node>
    - $TransferFunction = \frac{bodeout}{bodein}$
  - [6] Determine perturbing amplitude
    - <amp> set to a proper value
    - .option bodeampfreq=0 can force a constant perturbing amplitude (recommend to use this as initial run)









Basic Workflow of using .bode

- .bode simulation process
  - .tran simulation with CHIRP as perturbing source
    - Time to achieve steady state : *<TSETTLE>*
    - Perturbing source name : *<SOURCE>*
    - Perturbing source frequency range : *<FSTART>* and *<FEND>*
    - Perturbing source amplitude
      - *.option BODEAMPFREQ*: to determine *<AMP>* min amplitude frequency (!=0) or constant amplitude (=0)
      - *.option BodeLoPow* and *.option BodeHiPow*: to determine amplitude vs frequency profile
    - Relative tolerance : *.option BODETOL*
      - Lower value for longer perturbing source .tran duration
  - Deconvoluting time domain data with 9 threads
    - INPUT and OUTPUT nodes : *.option BODEIN* and *.option BODEOUT*
      - $\boldsymbol{TransferFunction = \frac{bodeout}{bodein}}$
    - OUTPUT nodes reference : *.option BODEREF* (default = Node 0 = GND)
    - Maximum deconvolution periods : *.option BODEPERIODS*
  - Applying aperture diffraction corrections

Study of syntax and .option parameters in .bode

.bode Syntax and .Option

syntax

Name	Description	Default
SOURCE[2]	Name of the perturbing voltage source inserted in the loop	No default but a value is required
TSETTLE[3]	Time required for the circuit to settle to steady state	No default but a value is required
FSTART[4]	Lowest frequency to analyze	1kHz
FSTOP	Highest frequency to analyze	1000 × FSTART
AMP[5]	Minimum amplitude of perturbing source	2mV

.option

Name	Description	Default
BODEAMPFREQ	Frequency with the minimum perturbation amplitude. Set to 0. for constant amplitude.	(not set)
BODEHIPOW	Controls perturbation amplitude for above BODEAMPFREQ by pow (freq/BODEAMPFREQ, BODEHIPOW)	1.
BODEINPUT[1]	Override input node for transfer function computation(AKA BODEIN)	auto
BODELOPOW	Controls perturbation amplitude for below BODEAMPFREQ by pow (freq/BODEAMPFREQ, BODELOPOW)	1.
BODEPERIODS	Maximum number of periods to include in deconvolution	20
BODEREF	Reference node to use for Frequency Response Analysis	Node 0 (global ground)
BODEOUTPUT[1]	Override output node for transfer function computation(AKA BODEOUT)	auto
BODETOL	A Frequency Response Analysis relative tolerance	10.

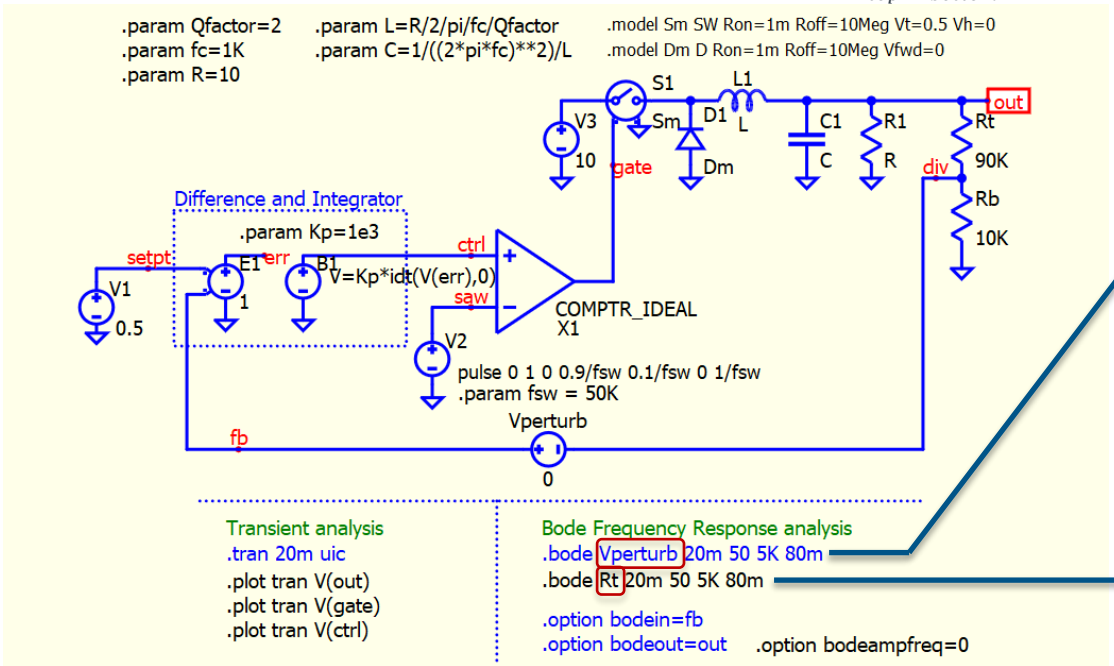
Hint

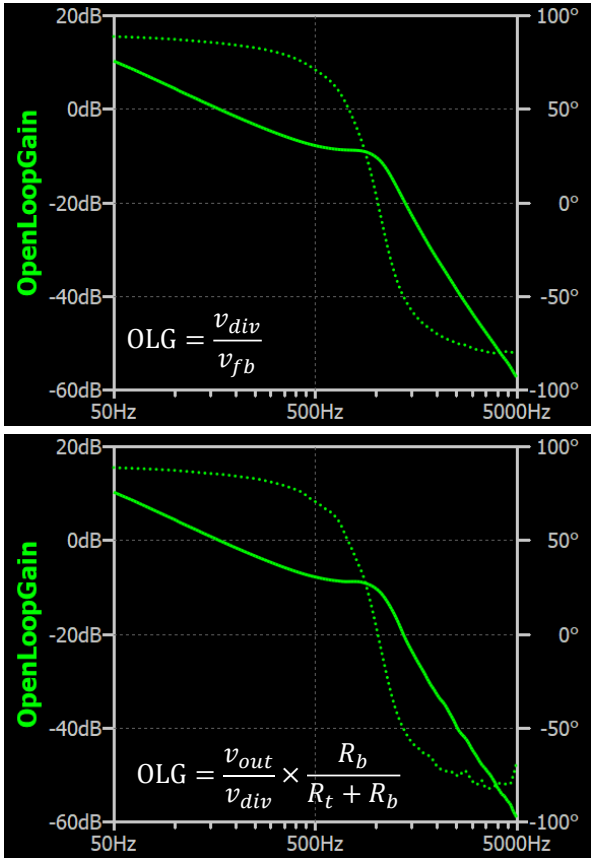
- Normally not need to change Bodetol and Bodeperiods
- First run set BodeAmpFreq=0 for constant amplitude perturbation
- Fstart and Fstop within 3 decade, and Fstart doesn't set at very low frequency
- To improve overall profile, may require varying perturbation amplitude, which requires use of Bodeampfreq / Bodehipow / Bodelipow for amplitude user defined amplitude profile.

Syntax <SOURCE>

Qspice : bode - Source.qsch

- <Source> can be voltage source or top resistor
  - If bodein and bodeout are not defined in .option
  - <Source> as voltage source : $OpenLoopGain = \frac{-ve\ terminal\ node}{+ve\ terminal\ node}$
  - <Source> as top resistor : $OpenLoopGain = \frac{resistor\ net\ 1\ node}{resistor\ net\ 2\ node} \times \frac{R_{top}}{R_{top}+R_{bottom}}$

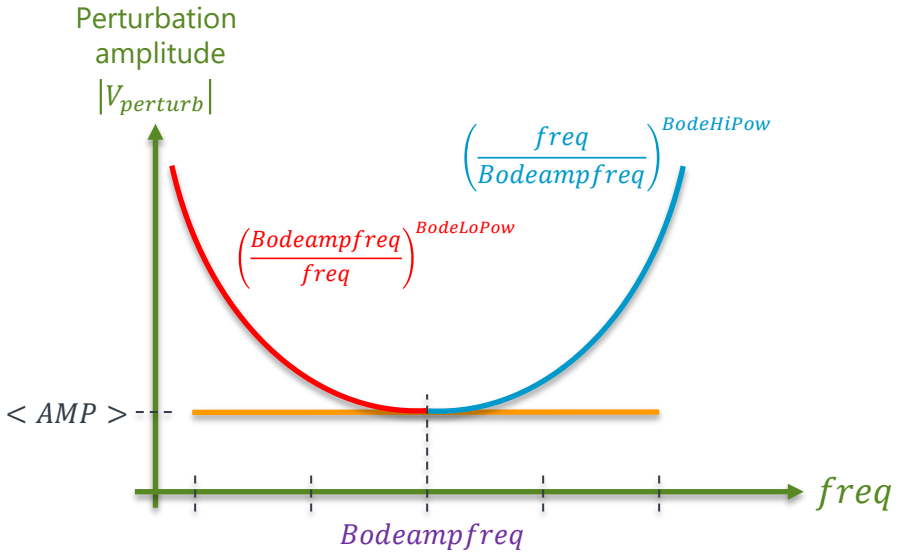




Syntax <AMP> and .option Bodeampfreq / BodeLoPow / BodeHiPow

- Perturbing Source Signal Amplitude
  - In close-loop perturbing, it requires flexibility to change its amplitude across test frequency to boost signal in high attenuation region or prevent controller saturation

- .option Bodeampfreq
  - If .option Bodeampfreq=0
    - $|V_{perturb}|$ for all frequency is unchanged = <AMP>
  - If .option Bodeampfreq is not defined
    - Default BodeAmpFreq $= 10^{\frac{\log_{10}(\text{Fstop})+\log_{10}(\text{Fstart})}{2}}$
  - If .option Bodeampfreq=<value>
    - BodeAmpFreq $= < f_{bodeampfreq} >$

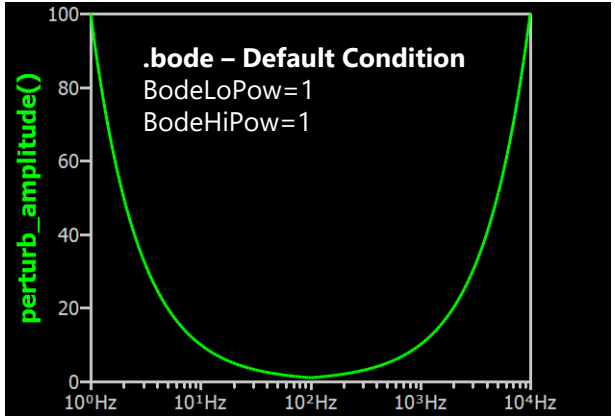


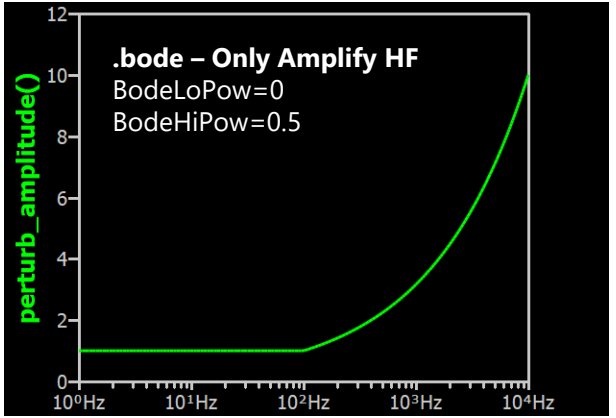
- .option BodeLoPow and BodeHiPow (Default as 1)
  - Assume $freq$ is between <Fstart> and <Fstop>
  - If $freq < Bodeampfreq$: $|V_{perturb}| =< AMP > \left(\frac{Bodeampfreq}{freq}\right)^{BodeLoPow}$
  - If $freq \geq Bodeampfreq$: $|V_{perturb}| =< AMP > \left(\frac{\frac{freq}{Bodeampfreq}}{}\right)^{BodeHiPow}$

Syntax <AMP> and .option Bodeampfreq / BodeLoPow / BodeHiPow

Qspice : bode - bodehipow bodelopow formula.qsch

- BodeLoPow / BodeHiPow
  - Formula is implemented in this schematic to demonstrate amplitude profile by changing BodeLoPow and BodeHiPow
  - ** In default, BodeLoPow=BodeHiPow=1
  - .option Bodeampfreq=0 force to constant amplitude



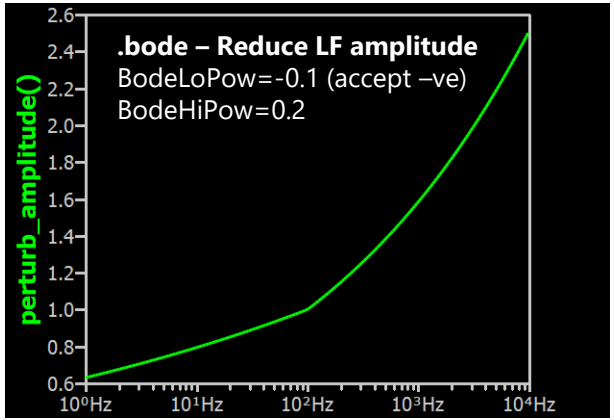


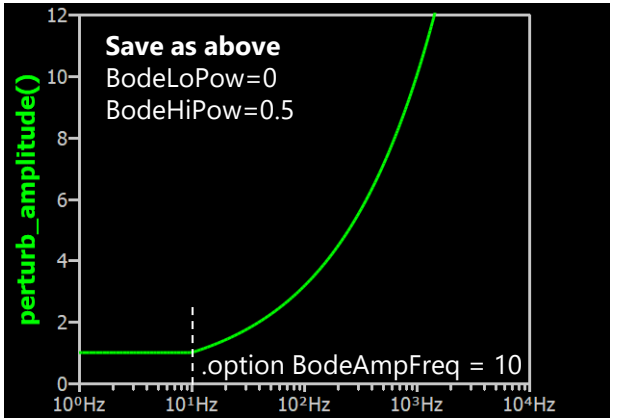
.bode and .option parameters

```
.param Amp = 1 ; [AMP] in .bode
.param Fstart = 1 ; [Fstart] in .bode
.param Fstop = 1e4 ; [Fstop] in .bode
.param BodeAmpFreq = pow(10,(log10(Fstop)+log10(Fstart))/2) ; default
.param BodeAmpFreq = 20 ; manual define BodeAmpFreq in .option

.param BodeLoPow = 1
.param BodeHiPow = 1
```

Calculate Amplitude vs Frequency Profile

```
.ac dec 100 Fstart Fstop

.func perturb_amplitude() AMP*if(Freq/BodeAmpFreq<1,
+pow(BodeAmpFreq/Freq, BodeLoPow),
+pow(Freq/BodeAmpFreq, BodeHiPow))

.plot perturb_amplitude()
```



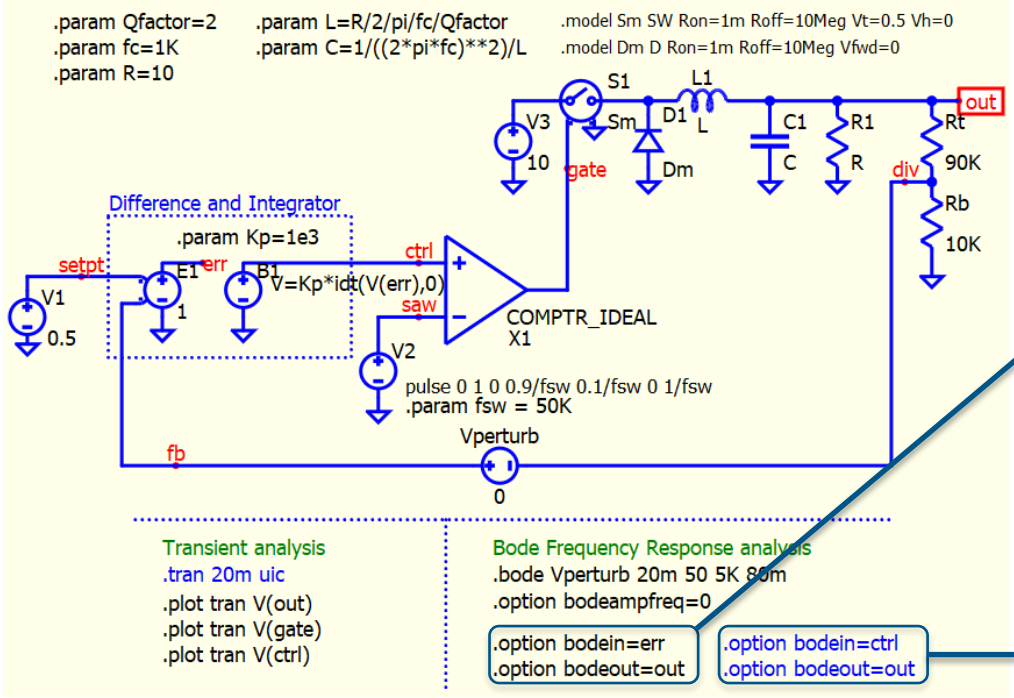


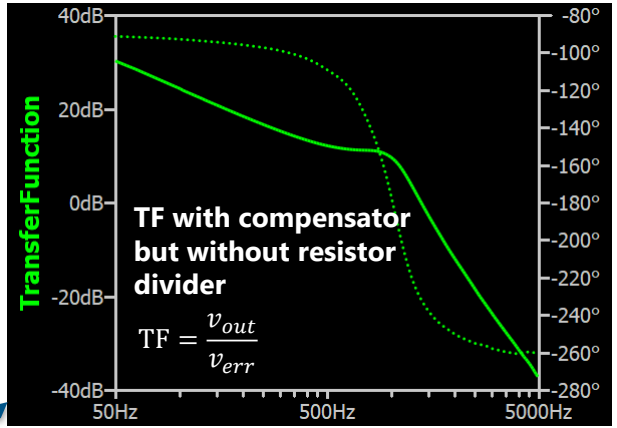
.option Bodein and Bodeout

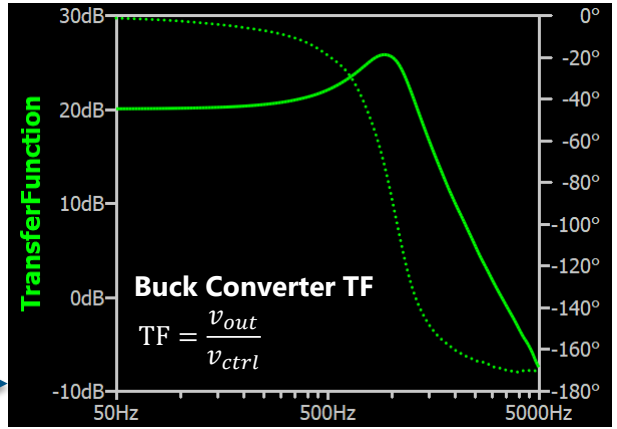
Qspice : bode - bodein bodeout.qsch

$$\text{TransferFunction} = \frac{\text{bodeout}}{\text{bodein}}$$

- Bodein and Bodeout
  - User can define voltage note name for bodein/bodeout params, result is store as TransferFunction



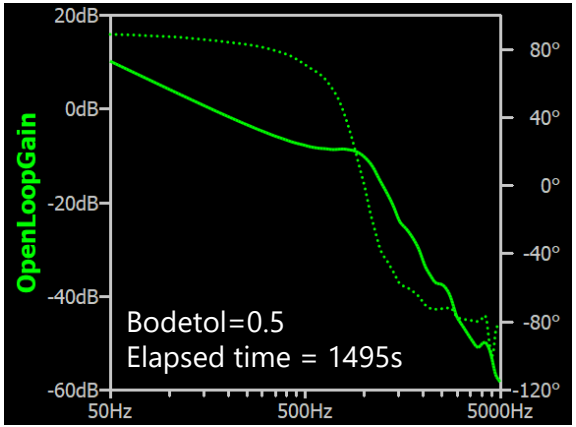


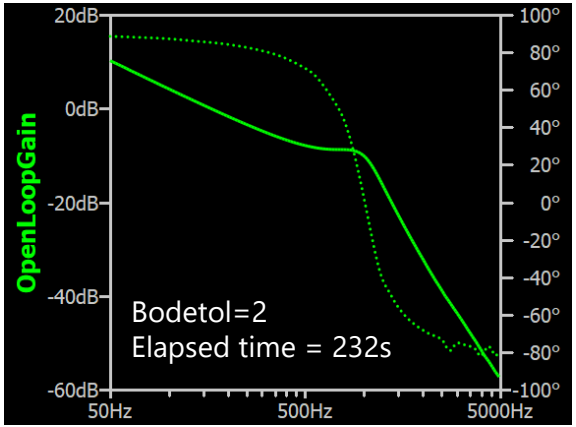


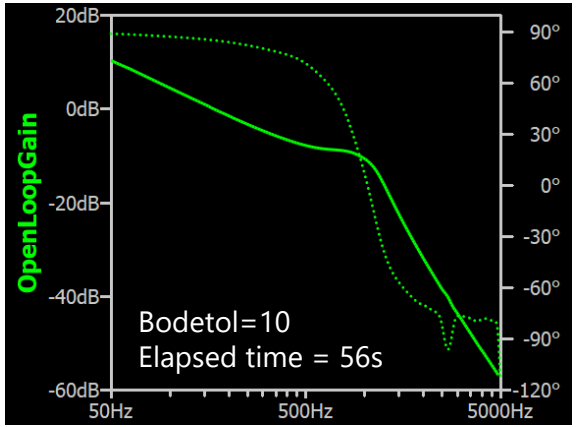
.option Bodetol

Qspice : bode - bodetol.qsch

- Bodetol : A frequency response analysis relative tolerance
  - Default Bodetol=10
    - Acceptable value from 0.1 to 15
  - Bodetol affects duration of time domain simulation during .bode
    - lower value = longer .tran duration = increase of simulation time
  - Reduce Bodetol may improve simulation results, but this is not guarantee if decrease too much

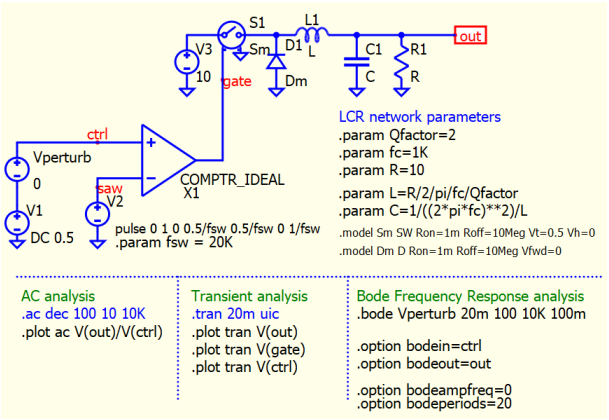


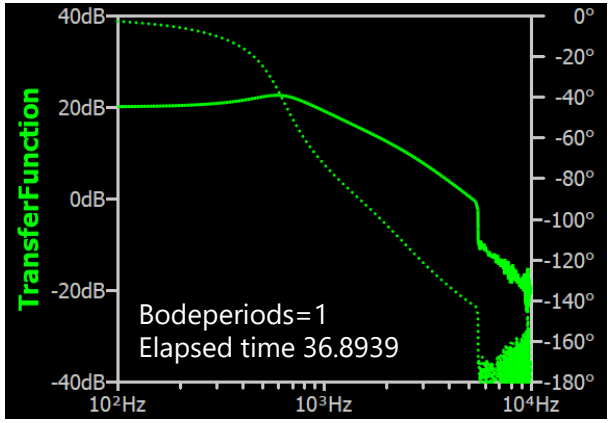


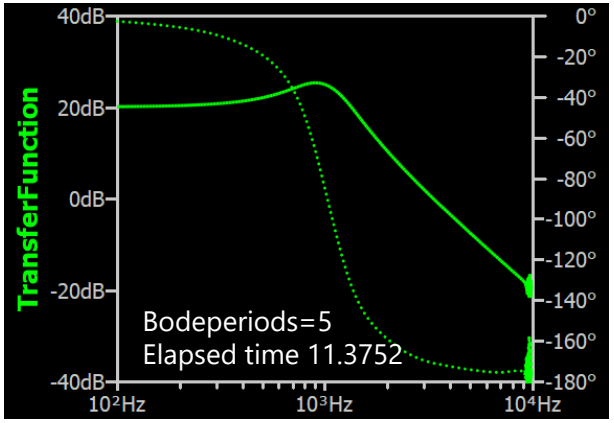


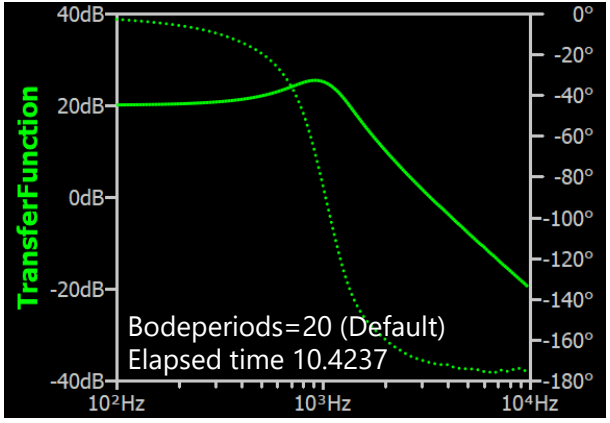
.option Bodeperiods

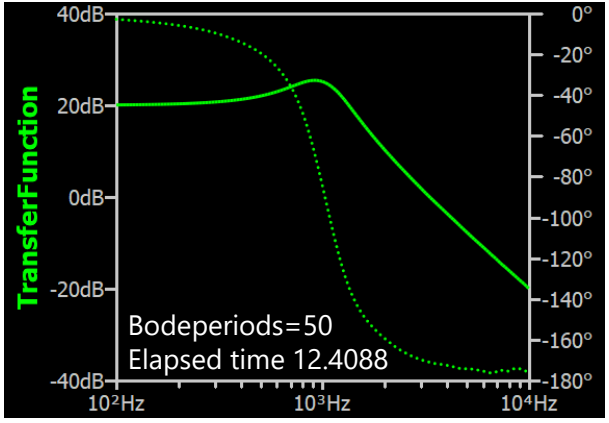
Qspice : bode - Buck - open loop - bodeperiods.qsch

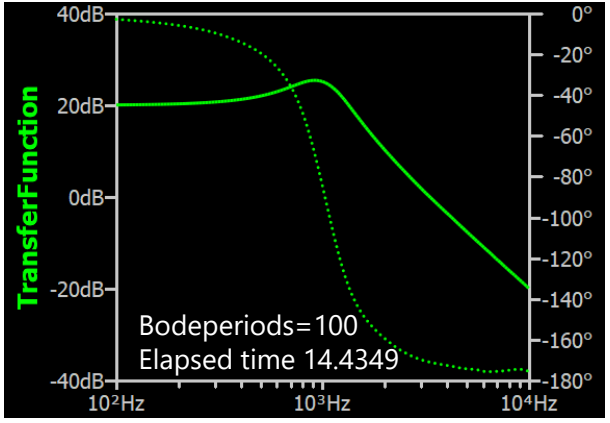












** I cannot identify it exact function, but setting in default can give a reasonable result

Explain .ac and .bode relationship

Basic of Frequency Response Analysis

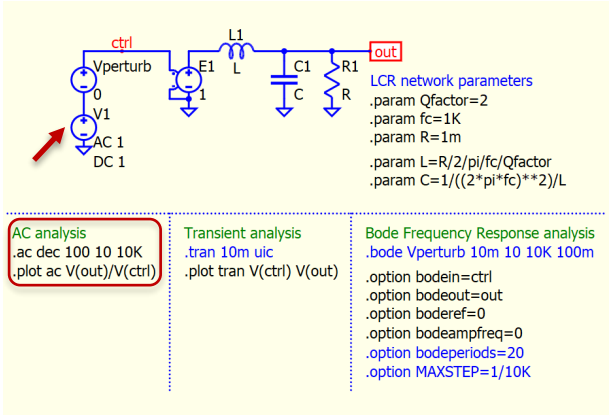
Qspice : Bode - LCR - open loop.qsch

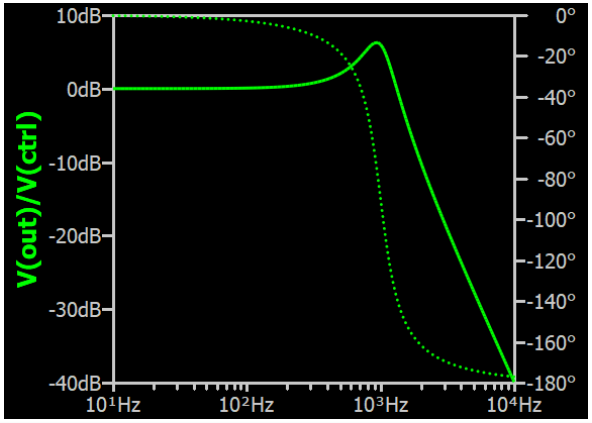
- Basic Theory
  - Frequency response analysis is to insert a perturbing source into system, and measuring gain/phase between two voltage nodes
  - .ac and .bode can achieve same result for linear circuit
  - In .ac example, V1 has AC 1 as perturbation source, and

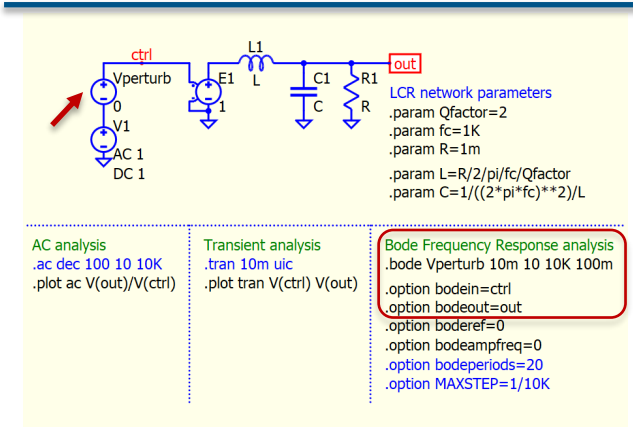
$$G(s) = \frac{v_{out}}{v_{ctrl}}$$

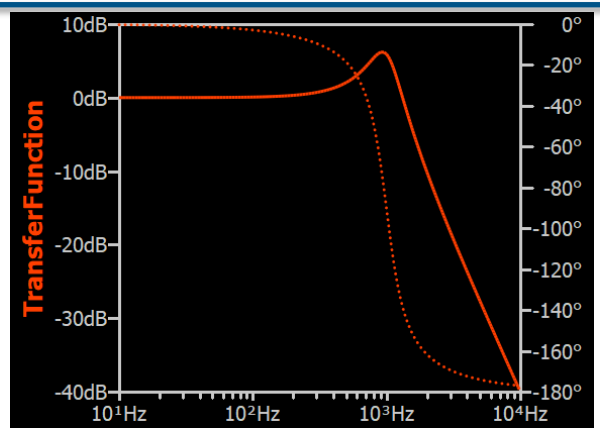
  - In .bode example, Vperturb is inserted with a setting that voltage equals 100mV from 10Hz to 10kHz

$$G(s) = \frac{\text{bodeout}}{\text{bodein}} = \frac{v_{out}}{v_{ctrl}}$$









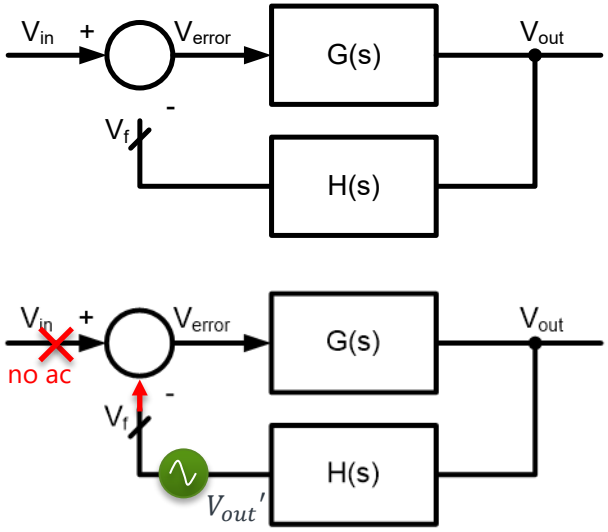
Open Loop Transfer Function in Close Loop System : Theory

- For close-loop system, perturbing source is added in feedback path to measure its open loop transfer function without breaking the close-loop operation

- Definition of Open Loop Transfer Function
  - It is defined as cutting the feedback path as
  - $GH(s) = G(s)H(s) = G_c(s)G_{plant}(s)H(s)$

- When V_f is break from the loop and AC test signal is from V_{in}
  - $GH(s) = \frac{output\ of\ H(s)}{input\ of\ G(s)} = \frac{\tilde{v}_f}{\tilde{v}_{in}} = \frac{\tilde{v}_f}{\tilde{v}_{error}}$

- If V_{in} is DC only and inject an AC to feedback path as test signal
  - $\tilde{v}_{error} = -\tilde{v}_f$
  - $GH(s) = \frac{output\ of\ H(s)}{input\ of\ G(s)} = \frac{\tilde{v}_{out}'}{\tilde{v}_{error}} = -\frac{\tilde{v}_{out}'}{\tilde{v}_f}$
  - If $H(s) = 1$, $V_{out} = V_{out}'$
    - $GH(s) = G_c(s)G_{plant}(s) = \frac{\tilde{v}_{out}}{\tilde{v}_{error}} = -\frac{\tilde{v}_{out}}{\tilde{v}_f}$

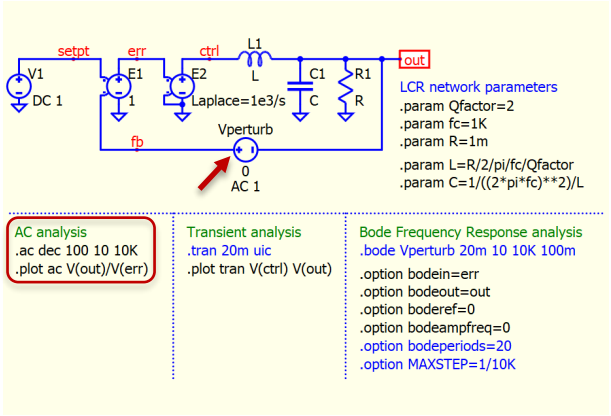


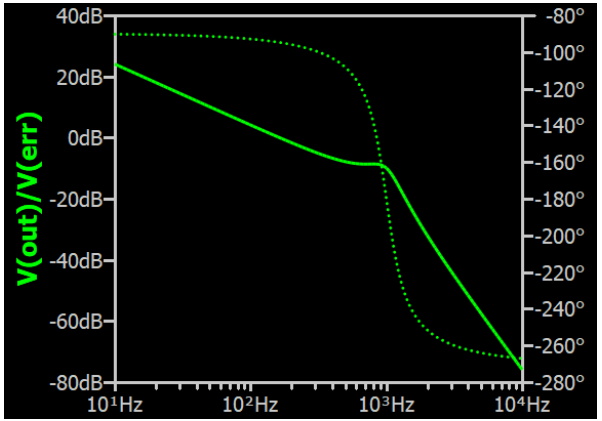
Open Loop Transfer Function in Close Loop System

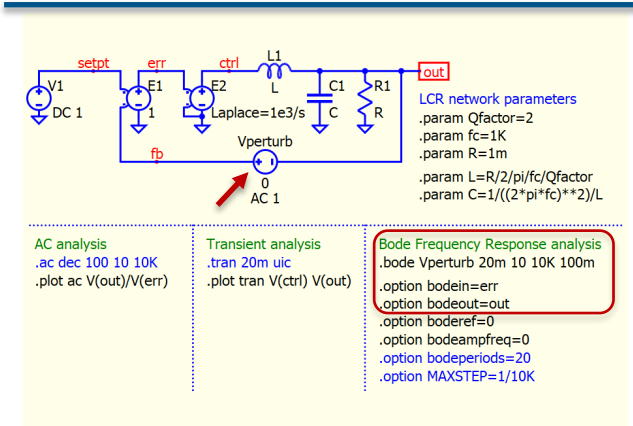
Qspice : Bode - LCR - open loop.qsch

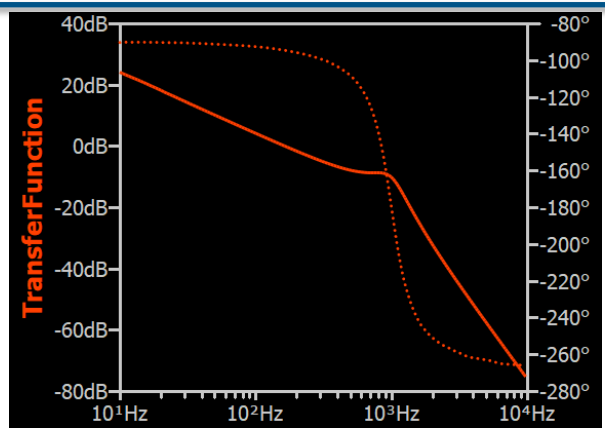
- Open Loop Transfer Function in Close Loop System
  - Perturbing source is inserted into feedback path
  - Open Loop Transfer Function $GH(s) = -\frac{v_{out}}{v_f} = \frac{v_{out}}{v_{err}}$
  - This is a linear system example, with E1 as difference and E2 as compensator (integrator), both .ac and .bode can be used in analyzing linear system

- Different of .ac and .bode
  - .ac only computes frequency response for non-switching circuit which can linearized
  - .bode extract frequency domain response from time domain analysis (.tran), to computes frequency response from switching circuit









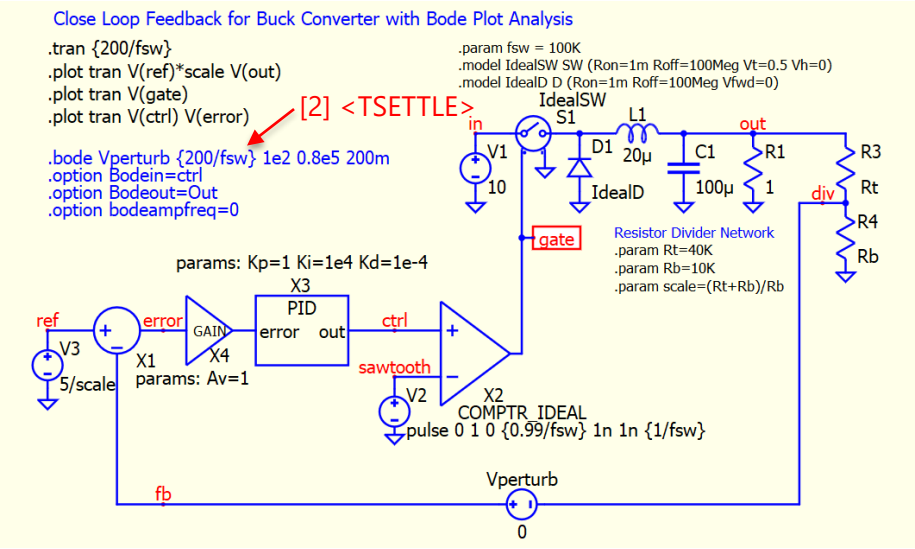
Appendix

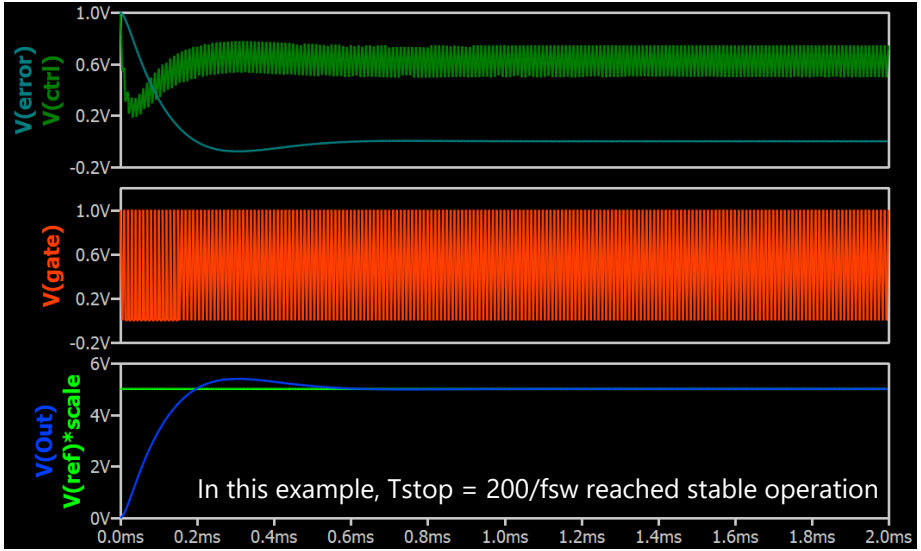
Step-by-Step Example
A Buck Converter

Part 1 : Close Loop Bode Plot Example

Qspice : Buck CloseLoop with Vperturb (.tran).qsch

- Determine <Tsettle>
  - [1] Run .tran analysis to determine how long the circuit can settle to steady state
    - .bode can only perform for a stable system
  - [2] Time required to reach stable operation is **<TSETTLE>** for .bode directive

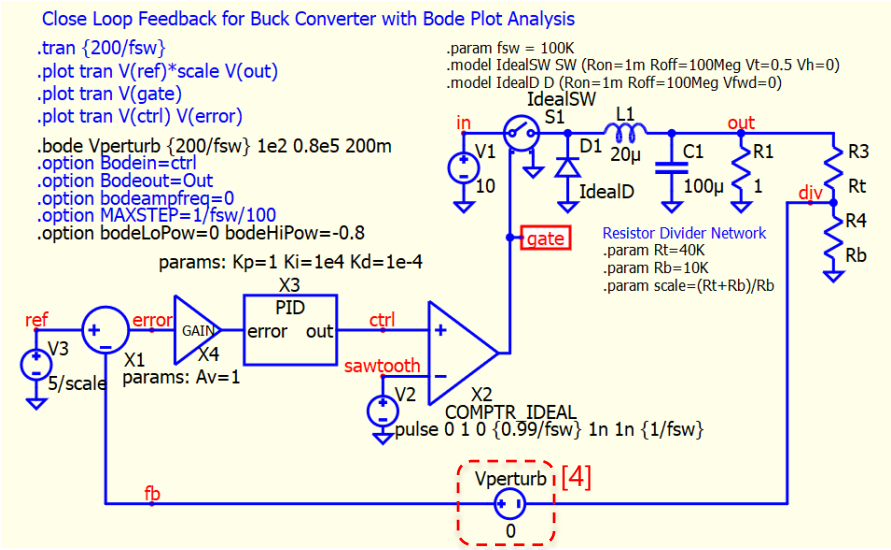


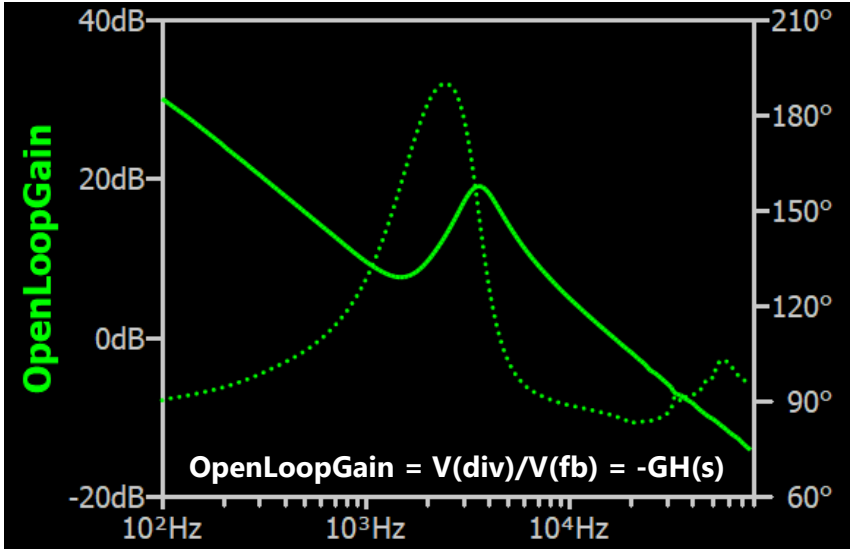


Part 1 : Close Loop Bode Plot Example - <SOURCE> is voltage source

Qspice : Buck CloseLoop with Vperturb (.bode).qsch

- .bode simulation with <SOURCE> is voltage source
  - [1] User determine **<FSTART>**, **<FSTOP>** and **<AMP>**, in this example, variable amplitude is used
  - [2] Perturbing source is added in series to feedback loop
    - If .option bodein and bodeout not specify
    - Bodeout is -ve terminal : transfer function numerator voltage node (e.g. div)
    - Bodein is +ve terminal : transfer function denominator voltage node (e.g. fb)
  - [3] Run simulation to get bode plot
    - If OpenLoopGain is not smooth, consider to adjust bodeLoPow and bodeHiPow for Amplitude <AMP> of perturbing source
    - If instability is observed at certain frequency, can use .option MAXSTEP to limit maximum time step in time domain analysis

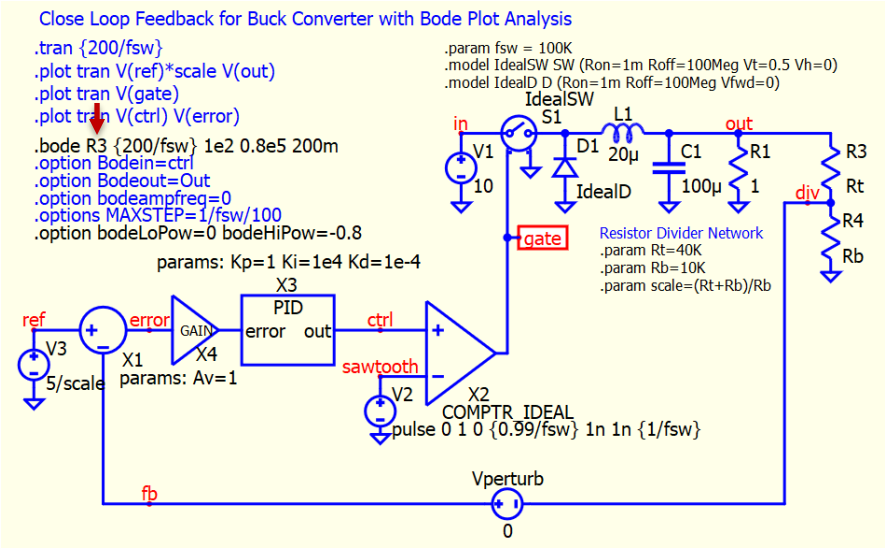


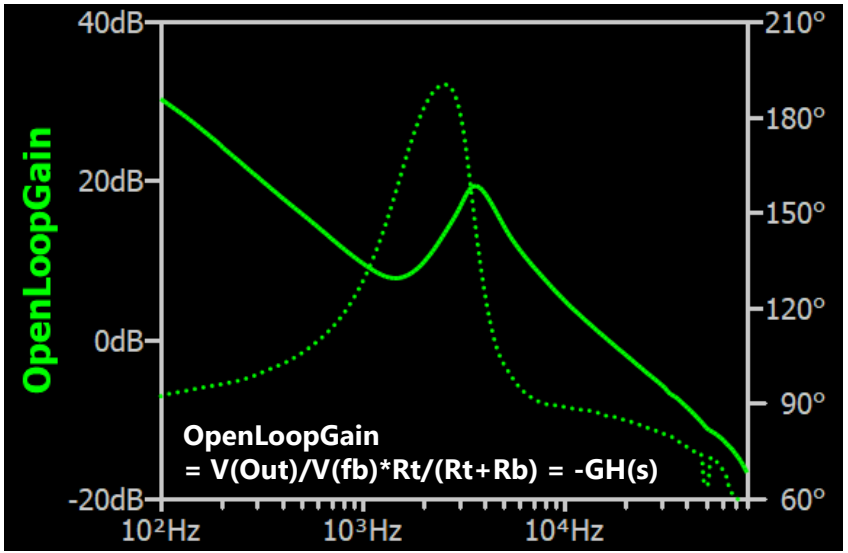


Part 1 : Close Loop Bode Plot Example - <SOURCE> is Top Resistor

Qspice : Buck CloseLoop with R3 (.bode).qsch

- .bode simulation with <SOURCE> is Top Resistor
  - [1] Alternatively, top resistor can be used as the perturbing source **<SOURCE>**
    - Resistor Pin 1 : transfer function numerator voltage node (e.g. out)
    - Resistor Pin 2 : transfer function denominator voltage node (e.g. div=fb)
  - [2] Run simulation to get bode plot

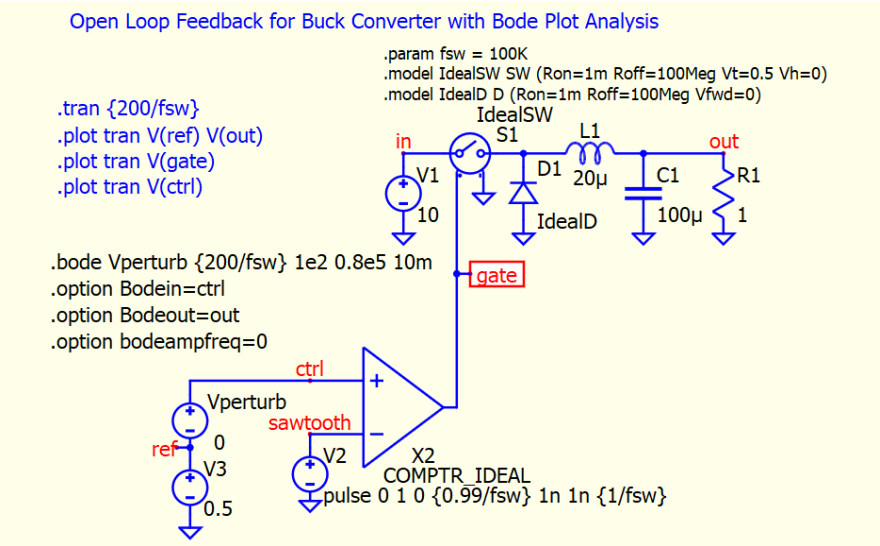


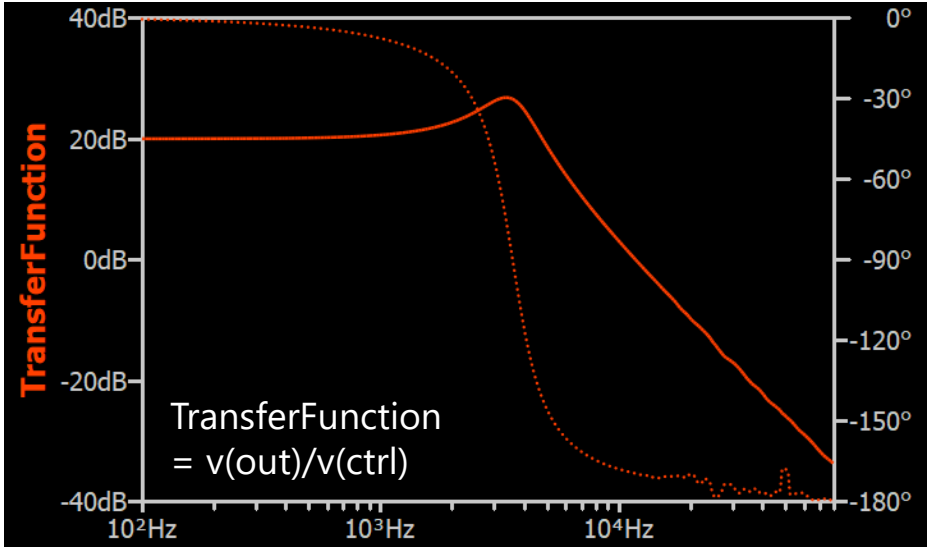


Part 2 : Open Loop Bode Plot Example

Qspice : Buck OpenLoop with Vperturb (.bode).qsch

- .bode for Open Loop
  - As numerator and denominator voltage node can be defined by in .option bodein / bodeout
  - [1] Arrange circuit into open loop operation, add perturbing source in series of reference/setpoint to input node (e.g. ctrl in this example)
  - [2] use .option to set input node with **.option Bodein** and output node with **.option Bodeout**
  - [3] Run simulation to get bode plot





Part 2 : Open Loop Bode Plot Example – C++ Comparator Block

Qspice : Buck ConverterBodePlot - OpenLoop with Cpp.qsch

- .bode for Open Loop with a C++ Comparator Block
  - This is to demonstrate .bode can work with digital blockset