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TEXAS INSTRUMENTS

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UCC39002 Load Share
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Power Supply Control Products

ENTER VARIABLES IN THE YELLOW AREAS; CALCULATED RESULTS ARE IN PINK AREAS

In the following example, two 3.3V, 10A modules are to be paralleled. The modules' remote sense has an adjustment range of 5% of the output voltage. The modules have an internal resistor between +Vout and Sense, R_{sense}, measured to be 200Ω. The modules have a measured band width of 2.4kHz, f_{comod}.

N_{units} is the number of paralleled units

$N_{units} := 2$

Useful identities

$m\Omega := 10^{-3}\cdot\Omega$

$mW := 10^{-3}\cdot W$

$S := \frac{1}{\Omega}$

STEP 1: Characterize the power module to be paralleled.

measured crossover frequency of the module. **Measure the BODE PLOT of the module as described in the UCC29002 data sheet**

$f_{comod} := 2.4\cdot kHz$

maximum output current of the module

$I_{outmax} := 14.8\cdot A$

output voltage of the module

$V_{out} := 54\cdot V$

maximum voltage adjustment of the module by way of the remote sense, usually given as a percentage in the module data sheet

$\Delta V_{outadjmax} := 0.02\cdot V_{out}$

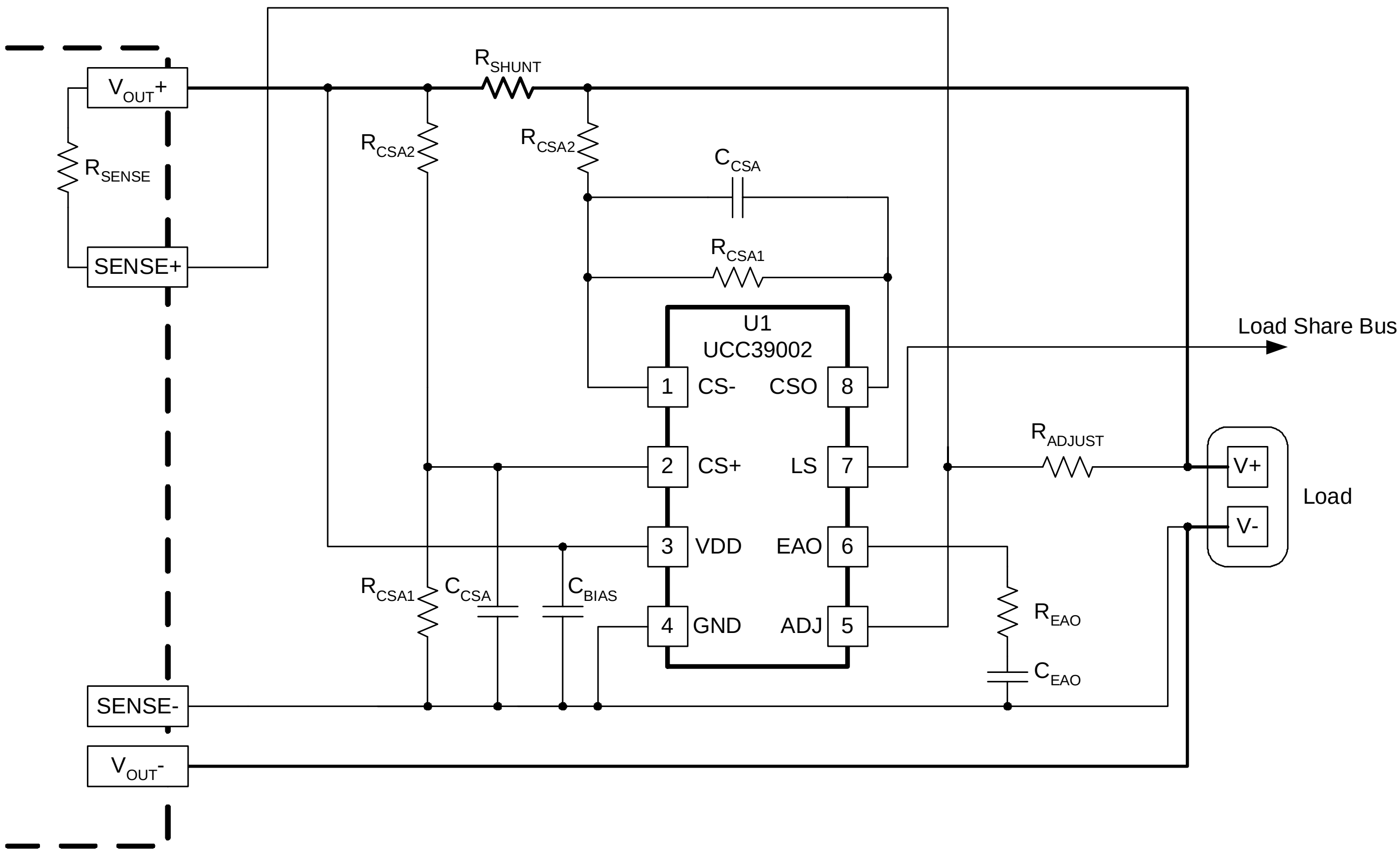
$\Delta V_{outadjmax} = 1.08\,V$

VDD input of the UCC39002

$V_{DD} := 12\cdot V$

Measured internal resistance between VOUT+ and SENSE+, R_{sense}

$$R_{sense} := 200000 \cdot \Omega$$



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STEP 2: Determine the Current Sense Resistor

Desired maximum power dissipation of the current sense resistor

$P_{Rshuntmax} := 0.8 \cdot W$

calculated maximum value of the current sense resistor, R_{shunt}, for the given allowable power dissipation

$$R_{shuntmax} := \frac{P_{Rshuntmax}}{I_{outmax}^{2}}$$

$R_{shuntmax} = 3.652 \cdot m\Omega$

standard resistor value used for current sensing

$R_{shunt} := 3.5 \cdot m\Omega$

calculated power dissipation of given sense resistor

$$P_{Rshunt} := R_{shunt} \cdot I_{outmax}^{2}$$

$P_{Rshunt} = 0.767\,W$

voltage drop across sense resistor (make sure it is less than the voltage adjustment range of the module and is much greater than the input voltage offset, 100µV, of the current sense amplifier)

$$V_{Rshunt} := I_{outmax} \cdot R_{shunt}$$

$V_{Rshunt} = 51.8 \cdot mV$

$\Delta V_{outadjmax} = 1.08 \cdot V$

although the drop across the current sense resistor is less than the usuable voltage adjustment range, it is a significant portion of it.

STEP 3: Set up the Current Sense Amplifier

Internal resistor at the LS pin

$R_{LS} := 100 \cdot k\Omega$ 内部阻抗100K

absolute max current sense amplifier output voltage before saturation, the master's V_{csa} determines the voltage of the load share bus

$V_{CSAo\_max} := V_{DD} - 2 \cdot V$

$V_{CSAo\_max} = 10\,V$

The output current of the LS driver is limited to 1mA, this relates to the maximum number of modules, N_{units}, to be paralleled to the LS voltage, N_{units_max}:

$I_{LSmax} := 1 \cdot mA$

$V_{LSmax} := V_{DD} - 1.7 \cdot V$

$$N_{units\_max} := \mathrm{floor}\left(\frac{R_{LS} \cdot I_{LSmax}}{V_{LSmax}}\right)$$

$N_{units\_max} = 9$

because V_{LS} is approximately equal to V_{csa} this just determines whether the number of modules in parallel exceeds the current capability of the LS driver; so long as V_{cso} is less than V_{LSmax} than everything is cool. Each slave module represents a load to the master based on the LS voltage and the 100kΩ internal resistor

$$I_{masterincreasemax} := N_{units} \cdot \left(\frac{V_{LSmax}}{R_{LS}}\right)$$

$I_{masterincreasemax} = 0.206 \cdot mA$

$P_{masterincrease} := V_{DD} \cdot I_{masterincreasemax}$

$P_{masterincrease} = 2.472 \cdot mW$

just keep this in mind for master IC bias current

the absolute allowable current sense gain before saturation, A_{CSAmax}

$$A_{CSAmax} := \frac{V_{CSAo\_max}}{R_{shunt} \cdot I_{outmax}}$$

$A_{CSAmax} = 193.05$

chosen current sense gain for this design, keeping well below the theoretical maximum calculated above:

$$A_{CSA} := 100$$

$$V_{CSAo} := A_{CSA} \cdot R_{shunt} \cdot I_{outmax}$$

$$V_{CSAo} = 5.18\,V$$

Gain set by Rcsa1 (parallel) and Rcsa2 (series)

$$R_{csa2} := 0.15 \cdot k\Omega$$

$$R_{csa1} := 15 \cdot k\Omega$$

$$A_{CSA\_actual} := \frac{R_{csa1}}{R_{csa2}}$$

resultant current sense amplifier output voltage and approximate LS bus voltage

$$A_{CSA\_actual} = 100$$

$$V_{CSAo\_actual} := A_{CSA\_actual} \cdot R_{shunt} \cdot I_{outmax}$$

$$V_{CSAo\_actual} = 5.18\,V$$

add a "high frequency" pole for noise roll off:

$$f_{pole} := 10 \cdot kHz$$

$$C_{CSA} := \frac{1}{2 \cdot \pi \cdot R_{csa1} \cdot f_{pole}}$$

$$C_{CSA} = 1.061 \cdot nF$$

Actual value of Ccsa:

$$C_{CSA\_actual} := 1000 \cdot pF$$

Resultant pole

$$f_{pole\_actual} := \frac{1}{2 \cdot \pi \cdot R_{csa1} \cdot C_{CSA\_actual}}$$

$$f_{pole\_actual} = 10.61 \cdot kHz$$

these compensation components must be on both input terminals of the differential amplifier

STEP 4: Determine the adjust resistor:

First meaure the internal resistance between $+V_{out}$ and +Sense.

$$R_{sense} = 2 \times 10^{5}\,\Omega$$

If we consider the voltage differential between $+V_{out}$ and +Sense to be equal to the voltage adgjustment range of the converter:

$$\Delta V_{outadjmax} = I_{sense} \cdot R_{sense}$$

and the adjustment range has been limited to:

$$\Delta V_{outadjmax} = 1.08\,V$$

Solve for I_{sense}

$$I_{sense} := \frac{\Delta V_{outadjmax}}{R_{sense}}$$

$$I_{sense} = 5.4 \times 10^{-3} \cdot mA$$

Because this internal resistor is essentially in parallel with the ADJ resistor, the ADJ amplifier current will be the sum of this I_{sense} and I_{Radj}

Internally the adjust pin is clamped to 3V and has a 500 Ohm emitter resistor which results in a maximum sink current at the adjust pin (data sheet functional block diagram shows 3V and 500Ω)

$$I_{adjmax} := \frac{3 \cdot V}{500 \cdot \Omega}$$

$$I_{adjmax} = 6 \cdot mA$$

Because V_{adj} must be greater than or equal to V_{eao}+1V, in order to keep the BJT on the adj from saturating, R_{adj} must be carefully selected. We know the master V_{eao} is 0V, therefore, since Adj is connected to the load bus through a resistor, V_{adj} is approximately equal to V_{BUS} and if V_{adj} must be V_{eao}+1V or greater, then the output bus voltage is limited to 1V minimum. Account for forward drop of oring diode if used.

$$V_{BUS} = V_{out} - I_{out} \cdot R_{shunt}$$

$$\Delta V_{outadjmax} = I_{sense} \cdot R_{sense}$$

$$I_{adj} = I_{sense} + I_{Radj}$$

$$I_{Radj} = I_{adj} - I_{sense}$$

$$I_{sense} \cdot R_{sense} = I_{out} \cdot R_{shunt} + I_{Radj} \cdot R_{adj}$$

$$I_{sense} \cdot R_{sense} = I_{out} \cdot R_{shunt} + \left(I_{adj} - I_{sense}\right) \cdot R_{adj}$$

Solve for I_{adj}:

$$I_{adj} = \frac{I_{sense} \cdot R_{sense} - I_{out} \cdot R_{shunt} + I_{sense} \cdot R_{adj}}{R_{adj}}$$

We know that V_{eao} will be approximately equal to:

$$V_{eao} = I_{adj} \cdot 500 \cdot \Omega$$

And the voltage on V_{adj} is equal to:

$$V_{adj} = V_{BUS} - R_{adj} \cdot I_{Radj}$$

$$V_{adj} = V_{out} - I_{out} \cdot R_{shunt} - R_{adj} \cdot I_{Radj}$$

And to keep the Adj BJT from saturating:

$$V_{adj} \geq V_{eao} + 1 \cdot V$$

Substituting leads to:

$$V_{out} - I_{out} \cdot R_{shunt} - R_{adj} \cdot I_{Radj} \geq I_{adj} \cdot 500 \cdot \Omega + 1 \cdot V$$

$$V_{out} - I_{out} \cdot R_{shunt} - R_{adj} \cdot \left(I_{adj} - I_{sense}\right) \geq I_{adj} \cdot 500 \cdot \Omega + 1 \cdot V$$

$$V_{out} - I_{out} \cdot R_{shunt} - R_{adj} \cdot \left(I_{adj} - I_{sense}\right) \geq I_{adj} \cdot 500 \cdot \Omega + 1 \cdot V$$

$$V_{out} - I_{out} \cdot R_{shunt} - R_{adj} \cdot I_{adj} + R_{adj} \cdot I_{sense} \geq I_{adj} \cdot 500 \cdot \Omega + 1 \cdot V$$

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which leads to:

$$V_{out} - I_{out} \cdot R_{shunt} - R_{adj} \cdot \frac{I_{sense} \cdot R_{sense} - I_{out} \cdot R_{shunt} + I_{sense} \cdot R_{adj}}{R_{adj}} + R_{adj} \cdot I_{sense} \geq \frac{I_{sense} \cdot R_{sense} - I_{out} \cdot R_{shunt} + I_{sense} \cdot R_{adj}}{R_{adj}} \cdot 500 \cdot \Omega + 1 \cdot V$$

$$V_{out} - I_{out} \cdot R_{shunt} - \left(I_{sense} \cdot R_{sense} - I_{out} \cdot R_{shunt} + I_{sense} \cdot R_{adj}\right) + R_{adj} \cdot I_{sense} \geq \frac{I_{sense} \cdot R_{sense} - I_{out} \cdot R_{shunt} + I_{sense} \cdot R_{adj}}{R_{adj}} \cdot 500 \cdot \Omega + 1 \cdot V$$

$$V_{out} - I_{out} \cdot R_{shunt} - I_{sense} \cdot R_{sense} + I_{out} \cdot R_{shunt} - I_{sense} \cdot R_{adj} + R_{adj} \cdot I_{sense} \geq \frac{I_{sense} \cdot R_{sense} - I_{out} \cdot R_{shunt} + I_{sense} \cdot R_{adj}}{R_{adj}} \cdot 500 \cdot \Omega + 1 \cdot V$$

$$V_{out} - I_{sense} \cdot R_{sense} \geq \frac{I_{sense} \cdot R_{sense} - I_{out} \cdot R_{shunt} + I_{sense} \cdot R_{adj}}{R_{adj}} \cdot 500 \cdot \Omega + 1 \cdot V$$

multiply both sides by Radj:

$$R_{adj} \cdot \left(V_{out} - I_{sense} \cdot R_{sense}\right) \geq \left(I_{sense} \cdot R_{sense} - I_{out} \cdot R_{shunt} + I_{sense} \cdot R_{adj}\right) \cdot 500 \cdot \Omega + 1 \cdot V \cdot R_{adj}$$

$$R_{adj} \cdot \left(V_{out} - I_{sense} \cdot R_{sense} - 1 \cdot V\right) \geq I_{sense} \cdot R_{sense} \cdot (500 \cdot \Omega) - I_{out} \cdot R_{shunt} \cdot (500 \cdot \Omega) + I_{sense} \cdot R_{adj} \cdot (500 \cdot \Omega)$$

$$R_{adj} \cdot \left(V_{out} - I_{sense} \cdot R_{sense} - 1 \cdot V - I_{sense} \cdot 500 \cdot \Omega\right) \geq I_{sense} \cdot R_{sense} \cdot (500 \cdot \Omega) - I_{out} \cdot R_{shunt} \cdot (500 \cdot \Omega)$$

$$R_{adj} \geq \frac{\left(I_{sense} \cdot R_{sense} - I_{out} \cdot R_{shunt}\right) \cdot 500 \cdot \Omega}{V_{out} - I_{sense} \cdot R_{sense} - 1 \cdot V - I_{sense} \cdot 500 \cdot \Omega}$$

In order to keep the internal bipolar from saturating, Radj must be greater than or equal to:

$$R_{adj\_veao} := \frac{\left(I_{sense} \cdot R_{sense} - I_{outmax} \cdot R_{shunt}\right) \cdot 500 \cdot \Omega}{V_{out} - I_{sense} \cdot R_{sense} - 1 \cdot V - I_{sense} \cdot 500 \cdot \Omega}$$

$$R_{adj\_veao} := \frac{\left(\Delta V_{outadjmax} - I_{outmax} \cdot R_{shunt}\right) \cdot 500 \cdot \Omega}{V_{out} - \Delta V_{outadjmax} - 1 \cdot V - \frac{\Delta V_{outadjmax}}{R_{sense}} \cdot 500 \cdot \Omega}$$

$$R_{adj\_veao} = 9.902\,\Omega$$

So R_{adj} must be **greater than or equal to this** to fulfill the V_{adj}-V_{eao} >/= 1V requirement. This requirement will automatically be met in higher voltage applications as shown in Figure 4 on the UCC29002 data sheet because V_{adj} will be within $1V_{BE}$ of VDD and VDD must be at least 4.75V.

the adjust resistor is also sized such that it operates over the available voltage adjustment current range of the module

$$I_{sense} \cdot R_{sense} = I_{out} \cdot R_{shunt} + \left(I_{adj} - I_{sense}\right) \cdot R_{adj}$$

$$R_{adj} = \frac{I_{sense} \cdot R_{sense} - I_{out} \cdot R_{shunt}}{I_{adjmax} - I_{sense}}$$

$$R_{adj\_Iadj} := \frac{\Delta V_{outadjmax} - I_{outmax} \cdot R_{shunt}}{I_{adjmax} - \dfrac{\Delta V_{outadjmax}}{R_{sense}}}$$

$$R_{adj\_Iadj} = 171.521\,\Omega$$

select R_{adj} such that it is large enough to fulfill the V_{adj}-V_{eao} is greater than or equal to 1V requirement AND results in an adjust current not greater than the 6mA limitation of the IC. Then calculate I_{adg}, V_{adj}, and V_{eao} to confirm that I_{adj} is not greater than 6mA, V_{adj} is greater than or equal to V_{eao}+1, and V_{eao} is not greater than 3V

selected R_{adj} value to meet both requirements

$$R_{adj} := 182 \cdot \Omega$$

$$I_{adj} := \mathrm{if}\left[\left(I_{adjmax} - I_{sense}\right) \cdot R_{adj} + I_{outmax} \cdot R_{shunt} > \Delta V_{outadjmax}, \frac{I_{sense} \cdot R_{sense} - I_{outmax} \cdot R_{shunt} + I_{sense} \cdot R_{adj}}{R_{adj}}, I_{adjmax}\right]$$

$$I_{adj} = 5.655 \cdot mA$$

In other words, there are two factors that are dependent: the I_{adj} and the ΔV_{outadj}. The I_{adj} maximum is determined by the 3.5V clamp and 500Ω resistor in the IC, ΔV_{outadj} maximum is limited by the module, neither of these can be exceeded but both can be lower than maximum. If it is determined that the max 7mA I_{adj} would result in a ΔV_{outadj} greater than the module is capable of, then I_{adj} is limited. Make sure V_{adj}>V_{eao}+1, and V_{eao}<3V

$$\Delta V_{outadj} := I_{outmax} \cdot R_{shunt} + \left(I_{adj} - I_{sense}\right) \cdot R_{adj}$$

$$\Delta V_{outadj} = 1.08\,V$$

$$V_{BE} := 0.7 \cdot V$$

$$V_{adj} := \begin{cases} V_{out} - I_{outmax} \cdot R_{shunt} - R_{adj} \cdot \left(I_{adj} - I_{sense}\right) & \text{if } V_{DD} < 15 \cdot V \\ V_{DD} - V_{BE} & \text{if } V_{DD} \geq 15 \cdot V \end{cases}$$

$$V_{adj} = 52.92\,V$$

$$V_{eao} := I_{adj} \cdot 500 \cdot \Omega$$

$$V_{eao} = 2.827\,V$$

$$V_{adj} - V_{eao} = 50.093\,V$$

BJT is saturating if V_{adj}-V_{eao}<1V

$$I_{adj\_amp} := \frac{I_{sense} \cdot R_{sense} - I_{outmax} \cdot R_{shunt} + I_{sense} \cdot R_{adj}}{R_{adj}}$$

$$I_{adj\_amp} = 5.655 \cdot mA$$

Now for the bode plots

$$R_{load} := \frac{V_{out}}{I_{outmax}}$$

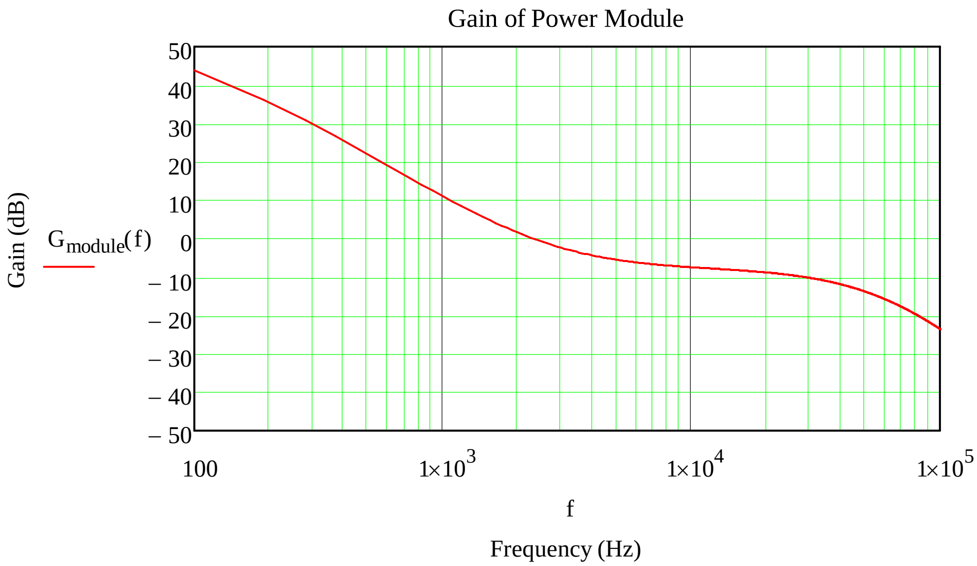
$$f := 10 \cdot Hz, 100 \cdot Hz .. 100 \cdot kHz$$

$$s(f) := j \cdot 2 \cdot \pi \cdot f$$

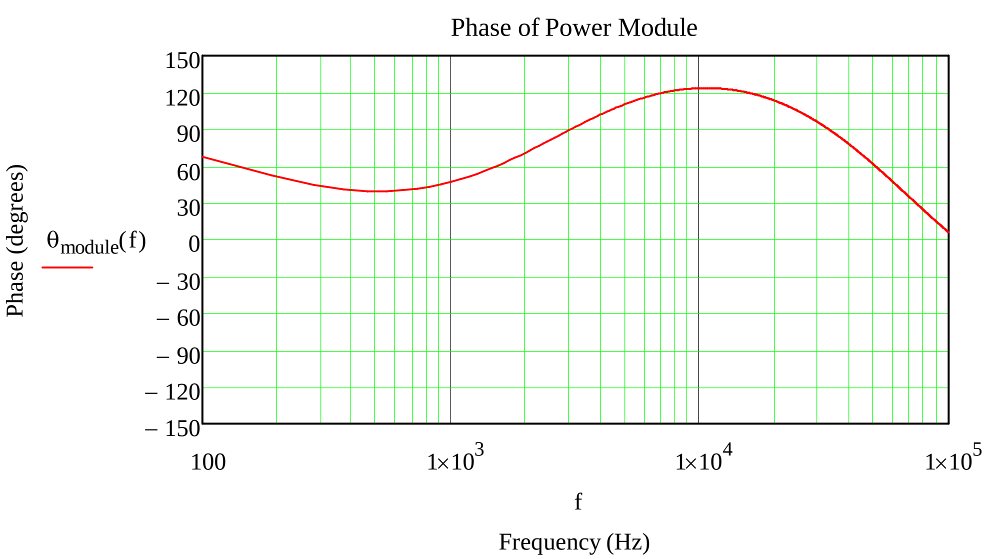
Based on the given Bode, the loop equation is derived and plotted to match measured plot...

$$G_{mod}(f) := 10^{\frac{71}{20}} \cdot \frac{\left[1 + s(f)\cdot\left(\frac{1}{2\cdot\pi\cdot 2.8\cdot kHz}\right)\right]^2}{\left[1 + s(f)\cdot\left(\frac{1}{2\cdot\pi\cdot 5\cdot Hz}\right)\right]\cdot\left[1 + s(f)\left(\frac{1}{2\cdot\pi\cdot 180\cdot Hz}\right)\right]\cdot\left[1 + s(f)\left(\frac{1}{2\cdot\pi\cdot 65\cdot kHz}\right)\right]^3}$$

$$G_{module}(f) := 20\cdot\log\left(\left|G_{mod}(f)\right|\right)$$



$$\theta_{module}(f) := \arg\left(G_{mod}(f)\right)\cdot\frac{180}{\pi} + 180$$



Want the total loop to cross at a decade or more befroe the module's crossover. To do this, determine what the gain of the module is at the desired system crossover frequency, determine the contribution from the open loop load share components, then select the error amplifier components to add the desired attenuation

$f_{comod} = 2.4 \cdot kHz$

$f_{CO} := 240 \cdot Hz$

SELECT THIS VALUE, f_{CO}, TO BE AT LEAST A DECADE BEFORE THE MEASURED f_{comod}

The gain of the module at the desired crossover frequency, in V/V:

$\left|G_{mod}\left(f_{CO}\right)\right| = 44.667$

or calculate from dB as taken from the Bode plot

$$10^{\frac{G_{module}\left(f_{CO}\right)}{20}} = 44.667$$

The gain of the module at the desired crossover frequency, in dB, which can be read directly from the Bode plot

$G_{module}\left(f_{CO}\right) := 20 \cdot \log\left(\left|G_{mod}\left(f_{CO}\right)\right|\right)$

$G_{module}\left(f_{CO}\right) = 33$

taking the Current sense amp into consideration:

$$G_{CSA}(f) := A_{CSA\_actual} \cdot \left[\frac{1}{1 + s(f) \cdot R_{csa1} \cdot \left(C_{CSA}\right)}\right]$$

$\left|G_{CSA}\left(f_{CO}\right)\right| = 99.971$

this is the actual gain over frequency but the pole is usually way beyond the module bandwidth and won't be a factor

$A_{CSA\_actual} = 100$

voltage gain

$$A_V := \frac{R_{shunt}}{R_{load}}$$

$A_V = 9.593 \times 10^{-4}$

Adjust amplifier gain

$$A_{ADJ} := \frac{R_{adj} \cdot R_{sense}}{\left(R_{adj} + R_{sense}\right) \cdot (500 \cdot \Omega)}$$

$$A_{ADJ} = 0.364$$

Internal Error amplifier transconductance

$$Gm := 0.014 \cdot S$$

open loop gain, converted to dB:

$$G_{openloop}(f) := \left(A_V \cdot A_{CSA\_actual} \cdot A_{ADJ}\right)$$

$$G_{openloop}\left(f_{CO}\right) = 0.035$$

Combining all of the known gains to determine the error amp compensation:

$$\left|G_{mod}\left(f_{CO}\right)\right| \cdot G_{openloop}\left(f_{CO}\right) \cdot G_{EA}\left(f_{CO}\right) = 1$$

$$G_{EA}\left(f_{CO}\right) := \frac{1}{\left|G_{mod}\left(f_{CO}\right)\right| \cdot G_{openloop}\left(f_{CO}\right)}$$

$$G_{EA}\left(f_{CO}\right) = 0.642$$

THIS IS THE VALUE OF GAIN, in dB, NEEDED FROM THE ERROR AMP COMPENSATION TO GET THE DESIRED CROSSOVER FREQUENCY

We know that the gain of a transconductance error amplifier is equal to:

$$G_{ErrorAmp}(f) = Gm \cdot \left(\frac{1}{s(f) \cdot C_{EAO}} + R_{EAO}\right)$$

Substituting for s:

$$G_{ErrorAmp}(f) = \left|Gm \cdot \left(\frac{1}{j \cdot 2\pi \cdot f_{CO} \cdot C_{EAO}} + R_{EAO}\right)\right|$$

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Assumption for C_{EAO}, should be a relatively large value due to the low frequency requirement:

$$C_{EAO} \ge \frac{Gm}{2\cdot\pi\cdot f_{CO}}\cdot\left(A_V\cdot A_{CSA\_actual}\cdot A_{ADJ}\cdot\left|G_{mod}(f_{CO})\right|\right)$$

to get a valid result for Reao, Ceao must be equal to or larger than this

$$C_{EAOmin} := \frac{Gm}{2\cdot\pi\cdot f_{CO}}\cdot\left(A_V\cdot A_{CSA\_actual}\cdot A_{ADJ}\cdot\left|G_{mod}(f_{CO})\right|\right)$$

$$C_{EAOmin} = 14.467\cdot\mu F$$

ASSIGN A VALUE FOR C_{EAO} BASED UPON TYPICAL AVAILABLE VALUES

$$C_{EAO} := 15\cdot\mu F$$

Solving for the magnitude of the resistance:

$$R_{EAO} := \sqrt{\left(-\frac{1}{j\cdot 2\pi\, f_{CO}\cdot C_{EAO}}\right)^2 + \left(\frac{G_{EA}(f_{CO})}{Gm}\right)^2}$$

$$R_{EAO} := \sqrt{\left(-\frac{1}{j\cdot 2\pi\, f_{CO}\cdot C_{EAO}}\right)^2 + \left[\frac{1}{Gm\cdot\left(\left|G_{mod}(f_{CO})\right|\cdot G_{openloop}(f_{CO})\right)}\right]^2}$$

$$R_{EAO} = 12.116\,\Omega$$

OR

$$R_{EAO} := \sqrt{\left[\frac{1}{Gm\cdot\left[\left|G_{mod}(f_{CO})\right|\cdot\left(A_V\cdot A_{CSA\_actual}\cdot A_{ADJ}\right)\right]}\right]^2 - \left(-\frac{1}{2\cdot\pi\cdot f_{CO}\cdot C_{EAO}}\right)^2}$$

$$R_{EAO} = 12.116\,\Omega$$

IS THIS A REAL OR IMAGINARY VALUE? IF IMAGINARY (CONTAINS i), SELECT ANOTHER VALUE FOR C_{EAO}

resultant actual zero frequency

THE CHOSEN C_{EAO} AND R_{EAO} COMPONENTS WILL PLACE A ZERO HERE

$$f_{ZERO} := \frac{1}{2 \cdot \pi \cdot R_{EAO} \cdot C_{EAO}}$$

$$f_{ZERO} = 0.876 \cdot kHz$$

Now Bode the whole thing:

$$G_{module}(f) := 20 \cdot \log\left(\left|G_{mod}(f)\right|\right)$$

$$Gain_{openloop}(f) := A_{CSA\_actual} \cdot A_V \cdot A_{ADJ} \cdot G_{mod}(f)$$

$$G_{openloop}(f) := 20 \cdot \log\left(\left|G_{CSA}(f)\right|\right) + 20 \cdot \log\left(\left|A_V\right|\right) + 20 \cdot \log\left(\left|A_{ADJ}\right|\right)$$

$$Gain_{ErrorAmp}(f) := Gm \cdot \left(\frac{1}{s(f) \cdot C_{EAO}} + R_{EAO}\right)$$

$$G_{EA}(f) := 20 \cdot \log\left(\left|Gain_{ErrorAmp}(f)\right|\right)$$

$$G_{total}(f) := G_{module}(f) + G_{openloop}(f) + G_{EA}(f)$$

THE FINAL RESULT SHOULD HAVE THE UNITY GAIN FOR THE TOTAL SYSTEM (BLACK) BEFORE THE ORIGINAL MODULE UNITY GAIN (RED), AND BE LINEAR. THE INDIVIDUAL CONTRIBUTIONS FROM THE OPEN LOOP COMPONENTS (PINK) AND ERROR AMP (BLUE) ARE ALSO SHOWN