



Variable Definition

$V_{in_min} := 85V$

$V_{in_max} := 265V$

$V_{out} := 390V$

$V_{ripple} := 30V$ Peak to Peak Output Ripple

$f_s := 50 \cdot 10^3 Hz$

$P_{out} := 1000W$ Maximum Output Power

$\eta := 0.90$ Maximum Output Efficiency at Low Line

$f_{line} := 47Hz$ Minimum Line Frequency

$thold_up := \frac{1}{f_{line}}$

$T_{amb} := 60$ Maximum Ambient Temperature Around Components

$V_{holdup} := 0.75 \cdot V_{out}$

$D_{max} := 0.97$ Maximum Duty Cycle Clamp

$f_{dm} := 30 \cdot 10^3 Hz$ Dither Magnitude

$f_{dr} := 10 \cdot 10^3 Hz$ Dither Rate

Fixed Variables

$V_{ref} := 3.0V$ $V_{INAC} := 3V$ $V_{IMO} := 3.3V$ $PKL := 3.3V$

I. Power Stage Design

1. Calculate min and maximum duty cycle

$$\frac{V_{out}}{V_{in}} = \frac{1}{1 - D}$$

Minimum duty cycle at peak inductor ripple current at low line

$$D_{p11} := \frac{V_{out} - V_{in_min} \cdot \sqrt{2}}{V_{out}}$$

$$D_{p11} = 0.692$$

Minimum D at Low Line

At crossover the duty cycle will be 100%

2. Estimate Interleaved Boost Input Ripple Current Cancellation with Changes in Duty Cycle

Inductor ripple current cancellation is similar to the output of a synchronous buck converter.

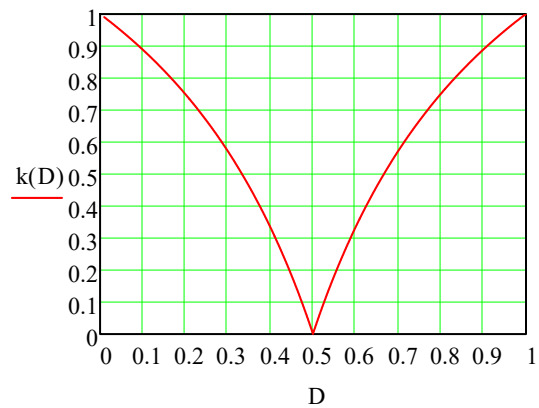
ΔI_{Cin} is the input capacitor ripple current

ΔI_L is the inductor ripple current

$$k(D) = \frac{\Delta I_{Cin}}{\Delta I_L}$$

$$D := 0.01, 0.011 \dots 1$$

$$k(D) := \begin{cases} \frac{1 - 2D}{1 - D} & \text{if } D \leq 0.5 \\ \frac{2 \cdot D - 1}{D} & \text{if } D > 0.5 \end{cases} \quad K(D) = \frac{\Delta I_{in}}{\Delta I_{L1}}$$



$$k(0.69) = 0.551$$

- a. The duty cycle of the converter will vary from 2.7% to 100%
- b. At peak inductor ripple current the duty cycle will be 0.69 which will have a 55% reduction in inductor ripple current seen at the input.

$$D_{pll} = 0.692$$

3. Size the boost Inductor at the peak of line for a converter input ripple current of 30%.

$$\Delta I_{in} = \Delta I_L \cdot K(D)$$

$$\Delta I_L = \frac{\Delta I_{in}}{K(D)}$$

$$\Delta I_L := \frac{P_{out} \cdot \sqrt{2} \cdot 0.3}{V_{in_min} \cdot \eta \cdot k(D_{pll})}$$

$$\Delta I_L = 10.003 \text{ A}$$

$$L_{boost} := \frac{V_{in_min} \cdot \sqrt{2} \cdot D_{pll}}{\Delta I_L \cdot f_s}$$

$$L_{boost} = L_1 = L_2$$

$$L_{boost} = 1.663 \times 10^{-4} \text{ H}$$

Choose a 140 uH inductor from Cooper Electronic Technologies

$$L_{boost_min} := 166.3 \cdot 10^{-6} \text{ H} \quad \text{Enter minimum inductance}$$

$$L_{boost_max} := 166.3 \cdot 10^{-6} \text{ H} \quad \text{Enter Maximum inductance}$$

$$L_{boost_avg} := \frac{L_{boost_max} + L_{boost_min}}{2}$$

$$L_{boost_avg} = 1.663 \times 10^{-4} \text{ H} \quad \text{Average inductance value to be used for current loop compensation}$$

4. Calculate Total Inductor RMS Current

$$IL1_RMS := \sqrt{\left(\frac{P_{out}}{2V_{in_min} \cdot \eta}\right)^2 + \frac{1}{\pi} \cdot \int_0^{\pi} \left(\frac{\frac{V_{in_min} \cdot \sqrt{2} \sin(\theta)}{L_{boost} \cdot f_s} \cdot \frac{V_{out} - V_{in_min} \cdot \sqrt{2} \sin(\theta)}{V_{out}}}{\sqrt{12}}\right)^2 d\theta}$$

$$IL1_RMS = 6.891 \text{ A}$$

5. Size the boost capacitor

a. First Criteria is how much holdup capacitance you need

$$V_{holdup} = 292.5 \text{ V}$$

$$P_{out} \cdot thold_up = \frac{C_{out} \cdot V_{out}^2}{2} - \frac{C_{out} \cdot V_{holdup}^2}{2}$$

$$C_{out} := 2 \cdot P_{out} \cdot \frac{thold_up}{V_{out}^2 - V_{holdup}^2}$$

$$C_{out} = 6.395 \times 10^{-4} \text{ F}$$

$$\underline{C_{out}} := 3.330 \cdot 10^{-6} \text{ F} = 9.9 \times 10^{-4} \text{ F} \quad \text{Choose a standar value}$$

$$\underline{V_{ripple}} := \frac{2P_{out}}{V_{out} \cdot \eta} \cdot \frac{1}{2 \cdot \pi \cdot 2 \cdot f_{line} \cdot C_{out}}$$

$$V_{ripple} = 9.745 \cdot \text{V}$$

b. Estimate Boost Capacitor RMS Current

$$I_{COUT_LF} := \frac{P_{out}}{V_{out} \cdot \eta \cdot \sqrt{2}} \quad \text{Total low frequency RMS current.}$$

$$I_{COUT_LF} = 2.015 \text{ A}$$

Calculate the high frequency component

$$I_{COUT_HF} := \sqrt{\left(\frac{P_{out}}{\eta \cdot V_{out}} \cdot \sqrt{\frac{16 \cdot V_{out}}{6 \cdot \pi \cdot V_{in_min} \cdot \sqrt{2}} - \eta^2} \right)^2 - I_{COUT_LF}^2}$$

$$I_{COUT_HF} = 3.423 \text{ A} \quad \text{Total low frequency RMS current.}$$

6. Calculate Peak FET and Boost Diode Current

$$I_{peak} := \left(\frac{\frac{P_{out} \cdot \sqrt{2}}{V_{in_min} \cdot \eta}}{2} + \frac{1}{2} \cdot \frac{V_{in_min} \cdot \sqrt{2} \cdot D_{pll}}{L_{boost} \cdot f_s} \right) \cdot 1.2 \quad \text{Peak Fet and Diode Current}$$

$$I_{peak} = 17.094 \text{ A}$$

7. Calculate Boost Switch RMS Current

$$I_{ds} := \frac{\frac{P_{out}}{\eta}}{2 V_{in_min} \cdot \sqrt{2}} \cdot \sqrt{2 - \frac{16 \cdot V_{in_min} \cdot \sqrt{2}}{3 \cdot \pi \cdot V_{out}}}$$

$$I_{ds} = 5.616 \text{ A}$$

8. Calculate Avarage Boost Diode Current

$$I_d := \frac{P_{out}}{2 V_{out}}$$

$$I_d = 1.282 \text{ A}$$

$$V_f := 1.25 \text{ V}$$

9. Current Sense Resistor and Transformer Set up

Calculate turns ratio based on peak FET current and peak current sense current

$$N_{ct} = \frac{N_s}{N_p} = \frac{V_s}{V_p} = \frac{I_{peak}}{I_{rs}}$$

$$I_{rs} := 0.1A$$

$$N_{ct} := \frac{I_{peak}}{I_{rs}} \quad I_{peak} = 17.094 A$$

$$N_{ct} = 170.935$$

$$N_{ct} := 200 \quad \text{Select 200 turns for the transformer(PCS040)}$$

$$a = \frac{1}{\frac{N_p}{N_s}}$$

$$a := \frac{1}{200} = 5 \times 10^{-3} \quad N_{ct} = \frac{N_s}{N_p} = \frac{V_p}{V_s} = \frac{I_{peak}}{I_{rs}}$$

Calculate Minimum Magnetizing Inductance

$$V_s := 3.7V$$

$$L_{mag} := \frac{V_s \cdot D_{pll}}{\frac{I_{peak}}{N_{ct}} \cdot 0.02 \cdot f_s}$$

$$L_{mag} = 0.03 H$$

Calculate Current Sense Resistor

$$R_s := \frac{V_s \cdot 0.9}{\frac{I_{peak}}{N_{ct}}}$$

$$R_s = 38.962 \Omega$$

$$R_s := 39\Omega \quad \text{Select Standard Value}$$

Select Reset Resistor

$$R_r := \frac{R_s \cdot D_{\max}}{1 - D_{\max}}$$

$$R_r = 1.261 \times 10^3 \Omega$$

 $R_r := 1300 \text{ ohm}$ Select Standard Value

Calculate Maximum Voltage Across R_r

$$V_{d\max} := \frac{I_{\text{peak}}}{N_{\text{ct}}} \cdot R_r$$

$$V_{d\max} = 111.108 \text{ V}$$

$$R_{pk1} := 3.6 \cdot 10^3 \text{ ohm}$$

$$R_{pk2} := \frac{V_s \cdot R_{pk1}}{6V - V_s}$$

$$I_{\text{peak}} = 17.094 \text{ A}$$

$$R_{pk2} = 5.791 \times 10^3 \Omega$$

 $R_{pk2} := 5.9 \cdot 10^3 \text{ ohm}$ Select Standard Value

10. Set up PWM Ramp to be added to current sense signal.

$$V_{CC} := 13 \text{ V}$$

$$V_{\text{off}} := 0.200 \text{ V}$$

Discontinues current sense signal offsetmduring discontinues operation when the gate drive turns on.

$$R_{oa} := \frac{R_s \cdot (V_{CC} - V_{\text{off}})}{V_{\text{off}}}$$

$$R_{oa} = 2.496 \times 10^3 \Omega$$

 $R_{oa} := 2.40 \cdot 10^3 \text{ ohm}$ Select Standard Value

$$\frac{V_{CC} - (V_s \cdot 0.1 - V_{off})}{R_{TA}} = \frac{V_s \cdot 0.1 - V_{off}}{R_s}$$

$$R_{TA} := \frac{[V_{CC} - (V_s \cdot 0.1 - V_{off}) + 0.6V] \cdot R_s}{V_s \cdot 0.1 - V_{off}}$$

$$R_{TA} = 3.081 \times 10^3 \Omega$$

$$R_{TA} := 3.0 \cdot 10^3 \text{ ohm} \quad \text{Select Standard Value}$$

$$C_{TA} := \frac{\frac{1}{f_s \cdot 3}}{R_s}$$

$$C_{TA} = 1.709 \times 10^{-7} \text{ F}$$

$$C_{TA} := 220 \cdot 10^{-9} \text{ F} \quad \text{Select Standard Value}$$

11. Set up Peak Current Limit

$$R_{pk1} := 3.6 \cdot 10^3 \text{ ohm}$$

$$R_{pk2} := \frac{V_s \cdot R_{pk1}}{6V - V_s}$$

$$R_{pk2} = 5.791 \times 10^3 \Omega$$

Select Standard Resistor

$$R_{pk2} := 5.9 \cdot 10^3 \text{ ohm}$$

12. Set up Controller Timing

Setup Oscillator Timing

$$R_{rt} := \frac{7.5 \times 10^9 \text{ ohm} \cdot \text{Hz}}{f_s}$$

$$R_{rt} = 1.5 \times 10^5 \Omega$$

$$R_{rt} := 150 \cdot 10^3 \text{ ohm} \quad \text{Select Standard Value}$$

Check Switching Frequency

$$f_s := \frac{7.5 \times 10^9 \text{ ohm} \cdot \text{Hz}}{R_{rt}}$$

$$f_s = 5 \times 10^4 \frac{1}{s}$$

Setup Duty Cycle Clamp

$$D_{max} := 0.97$$

$$R_{dmx} := R_{rt} \cdot (2 \cdot D_{max} - 1)$$

$$R_{dmx} = 1.41 \times 10^5 \Omega$$

Select Standard Resistor

$$R_{dmx} := 140 \cdot 10^3 \text{ ohm}$$

13. Voltage Loop Compensation

$$V_{ripple} = 9.745 \text{ V} \quad V_{ref} = 3 \text{ V} \quad g_m := 70 \cdot 10^{-6} \frac{\text{A}}{\text{V}} \quad \Delta V_{ea} := 3.2 \text{ V}$$

$$f := 1 \text{ Hz}, 2 \text{ Hz} \dots 1 \cdot 10^3 \text{ Hz}$$

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

$$R_A := 3 \cdot 10^6 \text{ ohm}$$

$$R_B := \frac{V_{ref} \cdot R_A}{V_{out} - V_{ref}}$$

$$R_B = 2.326 \times 10^4 \Omega$$

$$R_B := 24 \cdot 10^3 \text{ ohm}$$

Calculate OVP Trip Point

$$V_{ovp} := 3.18 \text{ V} \cdot \frac{R_A + R_B}{R_B}$$

$$V_{ovp} = 400.68 \text{ V}$$

$$\Delta V_{ea} \cdot 0.03 = \frac{V_{ripple} \cdot R_B}{R_A + R_B} \cdot g_m \cdot Z_f$$

$$Z_o := \Delta V_{ea} \cdot 0.03 \frac{1}{V_{ripple} \cdot 0.0077 \cdot g_m}$$

$$Z_o = 1.828 \times 10^4 \Omega$$

$$C_{pv} := \frac{1}{2 \cdot \pi \cdot 2f_{line} \cdot Z_o}$$

$$C_{pv} = 9.264 \times 10^{-8} \text{ F}$$

$$C_{pv} := 100 \cdot 10^{-9} \text{ F}$$

$$T(f) = 1 = \frac{R_2}{R_1 + R_2} \cdot g_m \cdot \left(\frac{\frac{P_{out}}{\eta}}{\Delta V_{ea}} \cdot \frac{\frac{1}{f \cdot C_{out}}}{V_{out}} \right) \cdot \frac{1}{2 \cdot \pi \cdot f \cdot C_{pv}}$$

$$f_c := \sqrt{\frac{R_B}{R_A + R_B} \cdot g_m \cdot \left(\frac{\frac{P_{out}}{\eta}}{\Delta V_{ea}} \cdot \frac{\frac{1}{2 \cdot \pi \cdot C_{out}}}{V_{out}} \right) \cdot \frac{1}{2 \cdot \pi \cdot C_{pv}}}$$

$$f_c = 11.25 \cdot \text{Hz}$$

$$\Delta V_{ea} = 3.2 \text{ V}$$

$$R_{zv} := \frac{1}{2 \cdot \pi \cdot f_c \cdot C_{pv}}$$

$$R_{zv} = 1.415 \times 10^5 \Omega$$

Select a standard resistor

$$R_{zv} := 150 \cdot 10^3 \text{ ohm}$$

$$R_{zv} = 1.5 \times 10^5 \Omega$$

$$C_{ZV} := \frac{1}{2 \cdot \pi \cdot \frac{f_c}{10} \cdot R_{ZV}}$$

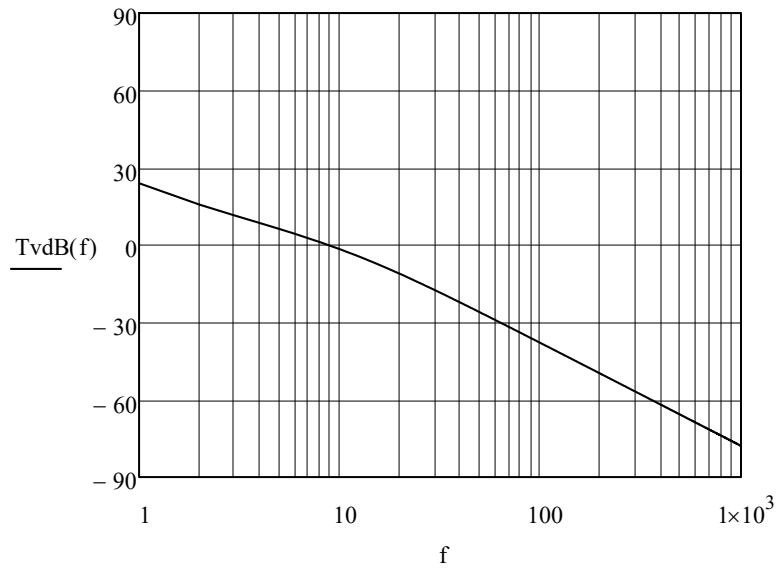
$$C_{ZV} = 9.432 \times 10^{-7} \text{ F}$$

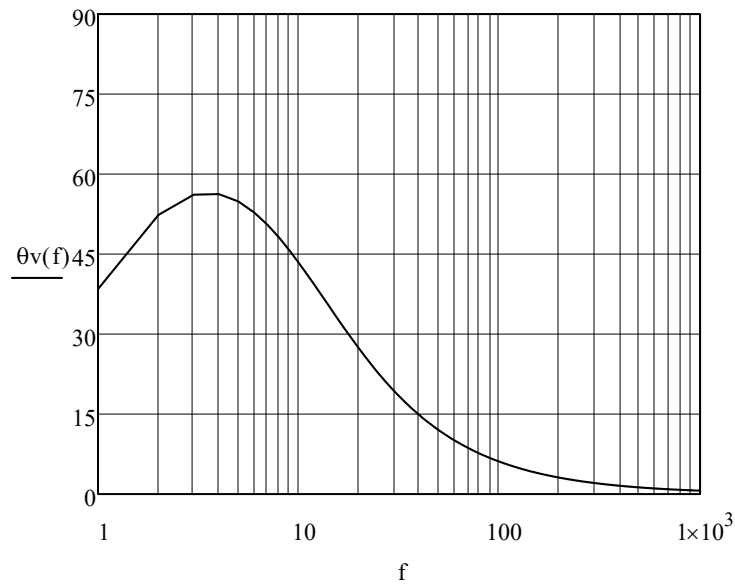
$$C_{ZV} := 1 \cdot 10^{-6} \text{ F}$$

$$\underline{T(f)} := \frac{R_B}{R_A + R_B} \cdot \text{gm} \cdot \left(\frac{\frac{P_{out}}{\eta}}{\Delta V_{ea}} \cdot \frac{1}{\frac{s(f) \cdot C_{out}}{V_{out}}} \right) \cdot \frac{s(f) \cdot R_{ZV} \cdot C_{ZV} + 1}{s(f) \cdot (C_{ZV} + C_{pv}) \cdot \left(\frac{s(f) \cdot R_{ZV} \cdot C_{ZV} \cdot C_{pv}}{C_{ZV} + C_{pv}} + 1 \right)}$$

$$\theta_v(f) := \arg(T(f)) \cdot \frac{180}{\pi} + 180$$

$$T_{vdB}(f) := 20 \cdot \log(|T(f)|)$$





$$\theta_v(9\text{Hz}) = 45.64$$

$$T_{\text{vdB}}(9\text{Hz}) = -0.348$$

14. Setup Current Loop

$$L_{\text{boost_max}} = 1.663 \times 10^{-4} \text{ H}$$

$$R_{\text{syn}} := \frac{L_{\text{boost_max}} \cdot \frac{R_B}{R_A + R_B}}{a \cdot R_s \cdot 0.1 \cdot 10^{-9} \text{ F}}$$

$$R_{\text{syn}} = 6.768 \times 10^4 \Omega$$

Select Standard Value

$$R_{\text{syn}} := 68 \cdot 10^3 \text{ ohm}$$

$$KVFF := 0.398 \text{ V}^2 \quad VAO_MAX := 5 \text{ V}$$

$$I_{\text{mo}} := \frac{0.76 \text{ V} \cdot 17 \cdot 10^{-6} \text{ A} \cdot (VAO_MAX - 1 \text{ V})}{KVFF}$$

$$I_{mo} = 1.298 \times 10^{-4} \text{ A}$$

$$V1 := 0.76V \cdot \frac{R_A + R_B}{R_B \cdot \sqrt{2}}$$

$$V1 = 67.713 \text{ V}$$

$$V_s := \frac{1.1 P_{out}}{2 \cdot \eta \cdot V1} \cdot \sqrt{2} \cdot a \cdot R_s$$

$$V_s = 2.489 \cdot V$$

$$R_{mo} := \frac{V_s}{I_{mo}}$$

$$R_{mo} = 1.917 \times 10^4 \Omega$$

$$R_{mo} := 20 \cdot 10^3 \text{ ohm}$$

Compensate Current Amplifier Compensation

$$g_m := 100 \cdot 10^{-6} \frac{\text{A}}{\text{V}}$$

Gain of the PFC Power Stage is:

$$V_{ramp} := 4.0 \text{ V}$$

$$G_{ps}(s) = \frac{V_{out} \cdot \frac{R_s}{N_{ct}}}{s \cdot L_{boost} \cdot V_{ramp}}$$

Solving for the power stage gain at the desired crossover frequency at 10th of the switching frequency.

$$f_c := \frac{f_s}{10} \quad f := 1 \text{ Hz}, 10 \text{ Hz} \dots 1 \cdot 10^6 \text{ Hz}$$

$$f_c = 5 \times 10^3 \cdot \text{Hz} \quad s(f) := 2j \cdot \pi \cdot f$$

$$L_{\text{boost_avg}} = 1.663 \times 10^{-4} \text{ H}$$

$$G_{\text{ps}} := \frac{V_{\text{out}} \cdot \frac{R_s}{N_{\text{ct}}}}{2 \cdot \pi \cdot f_c \cdot L_{\text{boost_avg}} \cdot V_{\text{ramp}}}$$

$$G_{\text{ps}} = 3.639$$

In order to have a gain of 1 at the crossover frequency the current amp must have a gain of $1/G_{\text{ps}}$ at the crossover frequency.

$$R_{\text{zc}} := \frac{1}{g_m \cdot G_{\text{ps}}}$$

$$R_{\text{zc}} = 2.748 \times 10^3 \Omega$$

$$C_{\text{zc}} := \frac{1}{2 \cdot \pi \cdot f_c \cdot R_{\text{zc}}}$$

$$C_{\text{zc}} = 1.158 \times 10^{-8} \text{ F}$$

$$C_{\text{pc}} := \frac{1}{2\pi \cdot \frac{f_s}{2} \cdot R_{\text{zc}}}$$

$$C_{\text{pc}} = 2.317 \times 10^{-9} \text{ F}$$

Select Standard Values

$$\underline{R_{\text{zc}}} := 2.7 \cdot 10^3 \text{ ohm}$$

$$\underline{C_{\text{zc}}} := 12 \cdot 10^{-9} \text{ F}$$

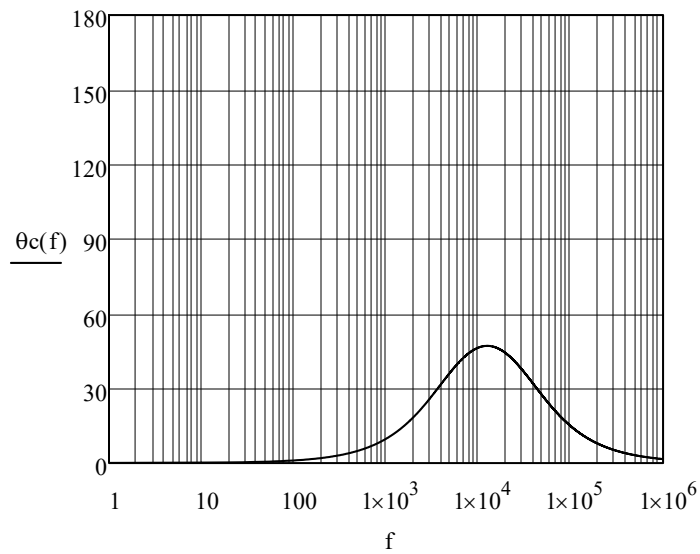
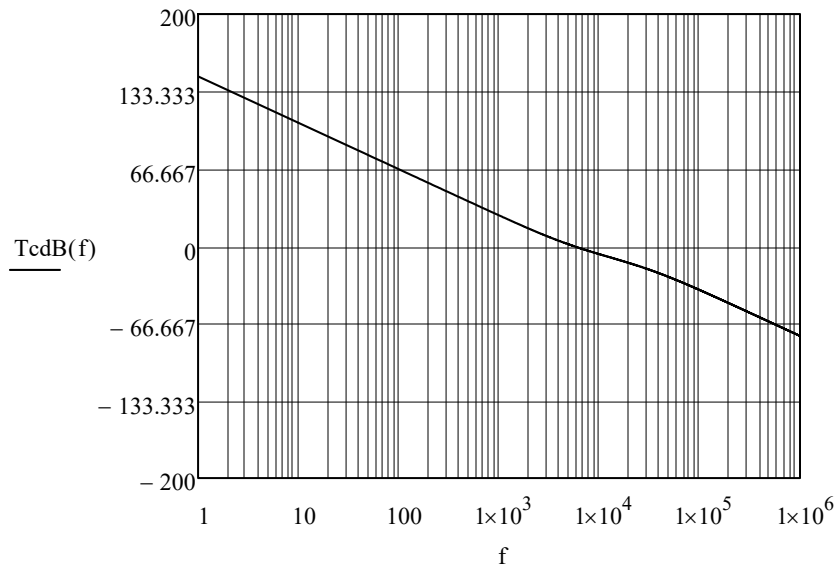
$$\underline{C_{\text{pc}}} := 2.2 \cdot 10^{-9} \text{ F}$$

Plot Loop Gain

$$\underline{\underline{T(f)}} := \frac{V_{out} \cdot R_s \cdot a}{s(f) \cdot L_{boost_avg} \cdot V_{ramp}} \cdot \left[g_m \cdot \frac{s(f) \cdot R_{zc} \cdot C_{zc} + 1}{s(f) \cdot (C_{zc} + C_{pc}) \cdot \left(\frac{s(f) \cdot R_{zc} \cdot C_{zc} \cdot C_{pc}}{C_{zc} + C_{pc}} + 1 \right)} \right]$$

$$\theta_c(f) := \arg(T(f)) \cdot \frac{180}{\pi} + 180$$

$$T_{dB}(f) := 20 \cdot \log(|T(f)|)$$



$$T_{dB}(20 \cdot 10^3 \text{ Hz}) = -14.857 \quad \theta_c(20 \cdot 10^3 \text{ Hz}) = 43.957$$

15. Soft Start

$$C_{ss} := \frac{10 \cdot 10^{-6} \cdot 0.2}{2.25}$$

$$C_{ss} = 8.889 \times 10^{-7}$$

Capacitor needs to be greater than or equal to C_{zv}

$$C_{zv} = 1 \times 10^{-6} \text{ F}$$

$$C_{ss} := 1 \cdot 10^{-6} \text{ F}$$

16. Dither Programming

$$R_{rdm} := 937.5 \cdot 10^6 \frac{\text{ohm}}{\text{fdm}} \quad \text{fdm} = 3 \times 10^4 \cdot \text{Hz}$$

$$R_{rdm} = 3.125 \times 10^4 \text{ H}$$

$$R_{rdm} := 47 \cdot 10^3 \text{ ohm} \quad \text{Select Standard Value}$$

$$C_{cdr} := 0.0667 \cdot 10^{-9} \text{ F} \cdot \frac{\text{Hz}}{\text{ohm}} \cdot \frac{R_{rdm}}{\text{fdr}}$$

$$C_{cdr} = 3.135 \times 10^{-10} \text{ F}$$

$$C_{cdr} := 330 \cdot 10^{-12} \text{ F} \quad \text{Select Standard Value}$$