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*****
**  NCP/NCV1362 Inductor and Losses calculation for adapter
**
**  /////////////////////////////////////////////////////////////////// **
**  Made by Yann Vaquette, email: yann.vaquette@onsemi.com for reporting any issue
**  Rev: 0.1    17/09/2020
**  Modifications: Initial Version
**      Rev 0.0: - Initial Release for NCP/NCV1362
**      Rev 0.1: - DC input voltage version
*****

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HOW TO USE THE SPREADSHEET

This spreadsheet will calculate for you every parameters needed to design a power supply using the NCP1362

Comment:

The zones underlined in pink need data from the user.

The zones underlined in yellow are calculation results

The zones underlined in red are controllers internal parameters and must not be changed !

INPUT DATA

Minimum DC input voltage: $V_{IN_{min}} := 120V$ Maximum DC input voltage: $V_{IN_{max}} := 375V$

Maximum output power: $P_{out} := 12W$ Output voltage: $V_{out} := 12V$

Estimated efficiency: $\eta := 85\%$ Output diode forward voltage: $V_f := 0.6V$

Switching frequency at maximum output power, low line: $F_{sw} := 50kHz$

External Capacitor between Drain & Source: $C_{DS} := 0.100pF$ External Cap for valley adjust

MOSFET part number: $FCU600N65S3R0$

MOSFET breakdown voltage: $BV_{dss} := 650V$

Mosfet C_{oss} @ $V_{DS} = V_o$: $C_{OSS} := 10pF$

Mosfet $V_{DS} = V_o$ @ which is measured $V_o := 400V$

Mosfet Q_g : $Q_g := 11nC$

MOSFET R_{dson} at $T_j = 110\text{ }^\circ\text{C}$: $R_{dson110} := 1.0\Omega$ (0.6 Ω max @ 25°C)

Output diode forward part number: $ON\ Semiconductor\ NRV\ TSS5100E$

Output diode forward voltage @ $T_j = 125\text{ }^\circ\text{C}$: $V_{f0} := 0.2V$

Controller Parameters:

Switching Frequency Clamp:

$$F_{sw_max} := 500\text{kHz}$$

Note: For no clamp option please enters Fsw_max >> to the max freq of your design, otherwise enters 80 kHz, 110 kHz or 140 kHz value

Maximum peak current:

$$V_{CSmax} := 0.8\text{V}$$

Frozen peak current in VCO mode:

$$V_{CSmin} := 250\text{mV}$$

Frozen peak current in VCO mode:

$$V_{CSmin2} := 65\text{mV}$$

Constant Current Voltage ref:

$$V_{ref_CC} := 1.0\text{V}$$

Internal min dead time in VCO:

$$DT_min := 650\text{ns}$$

$$K_{compCV} := K_{compCC} = 4$$

Minimal Fsw in VCO mode

$$F_{min} := 1\text{kHz}$$

Option 200 Hz or 1 kHz

Internal Comp Offset level

$$V_{CompOffset} := 1.1\text{V}$$

Min Comp pin level at which the peak current is frozen:

$$V_{CompIPKmin} := V_{CSmin} \cdot K_{compCV} + V_{CompOffset} = 2.1\text{V}$$

Min Comp pin level:

$$V_{Compmin} := 0.2\text{V}$$

Max Comp pin level:

$$V_{Compmax} := V_{CSmax} \cdot K_{compCV} + V_{CompOffset} = 4.3\text{V}$$

Total Propagation delay time:

$$t_{prop} := 150 \cdot \text{ns}$$

Internal Voltage reference

$$V_{ref_CV1} := 2.5\text{V}$$

$$V_{ref_OVP} := V_{ref_CV1} \cdot 126\% = 3.15\text{V}$$

$$V_{ref_UVP} := 1.5\text{V}$$

Transconductance gain:

$$g_m := 200 \frac{\mu\text{A}}{\text{V}}$$

Preliminary calculations:

$$I_{out} := \frac{P_{out}}{V_{out}}$$

$$I_{out} = 1\text{A}$$

Primary to secondary turn ratio calculation (Nps=Ns/Np)

MOSFET breakdown voltage:

$$BV_{dss} = 650\text{V}$$

Derating factor for the MOSFET breakdown voltage: $\alpha := 90\%$

Leakage inductance ratio ($k_{leak} = L_{leak} / L_p$)

$$k_{leak1} := 1.8\%$$

$$k_{leak2} := 2.0\%$$

$$k_{leak3} := 2.2\%$$

Clamping diode recovery time overshoot:

$$V_{os} := 10\text{V}$$

$$V_{DSmax} := BV_{dss} \cdot \alpha$$

$$V_{DSmax} = 585\text{V}$$

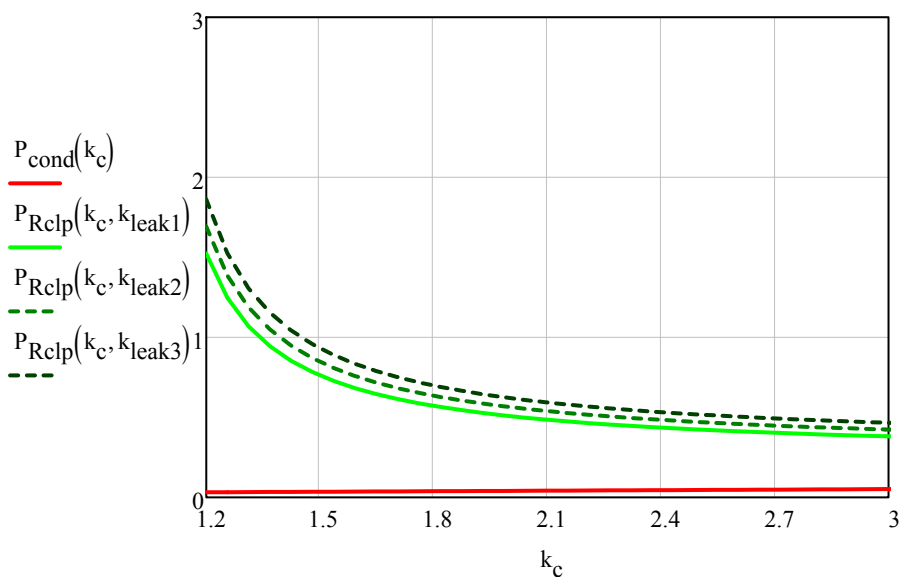
$$P_{\text{cond}}(k_c) := \frac{4}{3} \cdot R_{\text{dson}} \cdot I_{10}^2 \cdot \frac{P_{\text{out}}^2}{\eta^2 \cdot V_{\text{IN}_{\text{min}}}} \cdot \left[\frac{1}{V_{\text{IN}_{\text{min}}}} + \frac{k_c}{(V_{\text{DS}_{\text{max}}} - V_{\text{IN}_{\text{max}}} - V_{\text{os}})} \right]$$

$$P_{\text{Rclp}}(k_c, k_{\text{leak}}) := k_{\text{leak}} \cdot \frac{P_{\text{out}}}{\eta} \cdot \frac{k_c}{k_c - 1}$$

$$k_{c_min} := 1.2 \quad k_{c_max} := 4 \quad \text{nb_step} := 50$$

$$k_c := k_{c_min} + \frac{(k_{c_max} - k_{c_min})}{\text{nb_step}} \cdot i \quad \text{..} \quad k_{c_max}$$

The losses caused by the clamping resistor are plotted below for different value of kleak.



Clamping coefficient ($k_c = V_{\text{clamp}} / V_{\text{reflect}}$): $k_c := 1.9$

$$N_{\text{ps}_{\text{min}}} := \frac{k_c \cdot (V_{\text{out}} + V_f)}{(V_{\text{DS}_{\text{max}}} - V_{\text{os}} - V_{\text{IN}_{\text{max}}})} \quad N_{\text{ps}_{\text{min}}} = 0.12$$

Enter your value for Nps: $N_{\text{ps}} := 0.124$

New k_c based on the turn ratio selection if different from the theoretical calculation:

$$k_{c_{\text{new}}} := N_{\text{ps}} \cdot \frac{(V_{\text{DS}_{\text{max}}} - V_{\text{os}} - V_{\text{IN}_{\text{max}}})}{(V_{\text{out}} + V_f)} \quad k_c = 1.968$$

New V_{DS} of the Power MOS based on the Nps turn ratio selection:

$$V_{\text{DS}} := \frac{(V_{\text{out}} + V_f)}{N_{\text{ps}}} \cdot k_c + V_{\text{os}} + V_{\text{IN}_{\text{max}}} \quad V_{\text{DS}} = 585 \text{ V} \quad \text{must be } < \quad V_{\text{DS}_{\text{max}}} = 585 \text{ V}$$

$$V_{\text{clamp}} := \frac{(V_{\text{out}} + V_f)}{N_{\text{ps}}} \cdot k_c \quad V_{\text{clamp}} = 200 \text{ V}$$

Ipk and Lp calculation including the dead-time

$$I_{pk} := \frac{2 \cdot P_{out}}{\eta} \cdot \left(\frac{1}{V_{IN_{min}}} + \frac{Nps}{V_{out} + V_f} \right) + \pi \sqrt{\frac{2 \cdot P_{out} \cdot (C_{OSS} + C_{DS}) \cdot F_{sw}}{\eta}}$$

$I_{pk} = 0.525 \text{ A}$

$$L_p := \frac{2 \cdot P_{out}}{I_{pk}^2 \cdot \eta \cdot F_{sw}}$$

$L_p = 2.049 \cdot \text{mH}$

Enter your value for Lp:

$L_p := 1.2 \cdot \text{mH}$

Expected Leakage:

$k_{leak} := 1.8\%$

$I_{leak} := L_p \cdot k_{leak}$

$I_{leak} = 21.6 \cdot \mu\text{H}$

New Ipk value based on Lp selection

$$I_{pk_{new}} := \sqrt{\frac{2 \cdot P_{out}}{L_p \cdot \eta \cdot F_{sw}}}$$

$I_{pk} = 0.686 \text{ A}$

$$R_{sense_{CV}} := \frac{V_{CS_{max}}}{I_{pk}}$$

$R_{sense_{CV}} = 1.166 \cdot \Omega$

$V_{CS_{max}} = 0.8 \text{ V}$

$$V_{ref_CC_max} := V_{CS_{max}} \cdot 2 \cdot K_{compCC} \cdot Nps \cdot \sqrt{\frac{L_p \cdot \eta \cdot F_{sw} \cdot I_{out}}{2 \cdot V_{out}}} = 1.157 \text{ V}$$

$K_{compCC} \equiv 4$

$V_{ref_CC} := 1.0 \text{ V}$

$$I_{out_min} := \frac{2 \cdot V_{out} \cdot V_{ref_CC}^2}{(V_{CS_{max}} \cdot 2 \cdot K_{compCC} \cdot Nps)^2 \cdot L_p \cdot \eta \cdot F_{sw}} = 0.747 \text{ A}$$

R_{sense} calculation for CC regulation:

Maximum output current:

$I_{out_CC} := I_{out} = 1 \text{ A}$

$I_{out_CC_{CV}} := I_{out} \cdot 1.10 \quad I_{out} + 10\%$

$$R_{sense_theo} := \frac{V_{ref_CC}}{2 \cdot K_{compCC} \cdot Nps \cdot I_{out_CC}}$$

$R_{sense_theo} = 0.916 \cdot \Omega$

Enter the normalized value for Rsense:

$R_{sense} := R_{sense_theo} \cdot 99\% = 0.907 \Omega$

$R_{sense} := 0.907 \Omega$

New Iout value based on the R_{sense} selection:

$$I_{out_new} := \frac{V_{ref_CC}}{2 \cdot K_{compCC} \cdot Nps \cdot R_{sense}}$$

$I_{out_new} = 1.111 \text{ A}$

Auxiliary winding turn ratio

Desired value for VCC:

$$V_{CC} := 8V$$

Forward Voltage of Aux diode

$$V_{f_aux} := 0.8V$$

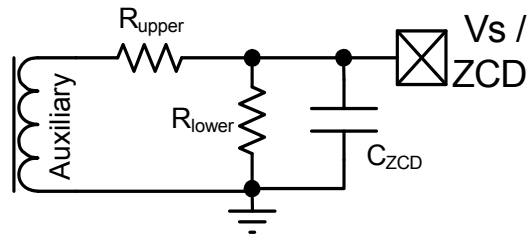
$$N_{aux} := \frac{N_{ps} \cdot (V_{CC} + V_{f_aux})}{V_{out} + V_{f0}}$$

$$N_{aux} = 0.089$$

Enter N_{aux} value:

$$N_{aux} := 0.089$$

ZCD resistor divider calculation:



Max voltage on Aux winding

$$V_{aux} := (V_{out} + V_{f0}) \cdot \frac{N_{aux}}{N_{ps}}$$

$$V_{aux} = 8.756 V$$

Constant time selection, must be below 100 ns in order to keep a good accuracy on the CV regulation:

$$\tau := 0.100 \mu s$$

Arbitrary Selection of Rupper on ZCD pin:

$$R_{upper} := 9.29 k\Omega$$

$$R_{lower} := R_{upper} \frac{V_{ref_CV1}}{(V_{aux}) - V_{ref_CV1}}$$

$$R_{lower} = 3.712 \cdot k\Omega$$

$$C_{ZCD} := \frac{R_{upper} + R_{lower}}{R_{upper} \cdot R_{lower}} \cdot \tau$$

$$C_{ZCD} = 37.703 \cdot pF$$

$$M := \frac{V_{ref_CV1}}{V_{aux} - V_{ref_CV1}} = 0.4$$

R_{lower} components values selection:

$$R_{lower} := 4.3 k\Omega$$

$$C_{ZCD} := \frac{R_{upper} + R_{lower}}{R_{upper} \cdot R_{lower}} \cdot \tau = 34.02 \cdot pF$$

C_{zcd} components values selection:

$$C_{ZCD} := 10 pF$$

Time constant verification

$$\tau := \frac{R_{\text{upper}} \cdot R_{\text{lower}}}{R_{\text{upper}} + R_{\text{lower}}} \cdot C_{\text{ZCD}}$$

$$\tau = 0.029 \cdot \mu\text{s}$$

Output voltage error based on the R_{lower} and R_{upper} selection:

$$M := \frac{R_{\text{lower}}}{R_{\text{upper}}} = 0.463$$

$$V_{\text{out_Error}} := \frac{V_{\text{ref_CV1}} - V_{\text{aux}} \cdot \frac{M}{1 + M}}{V_{\text{ref_CV1}}}$$

$$V_{\text{out_Error}} = -10.825\%$$

V_{out} OVP & UVP protection level with resistor divider selection:

$$V_{\text{out_OVP}} := \frac{N_{\text{ps}}}{N_{\text{aux}}} \cdot \frac{(R_{\text{upper}} + R_{\text{lower}})}{R_{\text{lower}}} \cdot V_{\text{ref_OVP}}$$

$$V_{\text{out_OVP}} = 13.871 \text{ V}$$

$$V_{\text{out_UVP}} := \frac{N_{\text{ps}}}{N_{\text{aux}}} \cdot \frac{(R_{\text{upper}} + R_{\text{lower}})}{R_{\text{lower}}} \cdot V_{\text{ref_UVP}}$$

$$V_{\text{out_UVP}} = 6.605 \text{ V}$$

Primary and secondary rms current calculation

$$T_{\text{on_max}} := \frac{I_{\text{pk}} \cdot L_{\text{p}}}{V_{\text{IN_min}}}$$

$$T_{\text{on_max}} = 6.86 \cdot \mu\text{s}$$

$$D_{\text{max}} := T_{\text{on_max}} \cdot F_{\text{sw}}$$

$$D_{\text{max}} = 34.3\%$$

$$I_{\text{pRMS}} := I_{\text{pk}} \cdot \sqrt{\frac{1 \cdot D_{\text{max}}}{3}}$$

$$I_{\text{pRMS}} = 0.232 \text{ A}$$

$$I_{\text{ps}} := \frac{I_{\text{pk}}}{N_{\text{ps}}}$$

$$I_{\text{ps}} = 5.532 \text{ A}$$

$$I_{\text{sRMS}} := I_{\text{ps}} \cdot \sqrt{\frac{1}{3} \cdot (1 - D_{\text{max}})}$$

$$I_{\text{sRMS}} = 2.589 \text{ A}$$

$$I_{\text{priDC}} := I_{\text{pk}} \cdot \frac{D_{\text{max}}}{2}$$

$$I_{\text{priDC}} = 0.118 \text{ A}$$

$$I_{\text{priAC}} := \sqrt{I_{\text{pRMS}}^2 - I_{\text{priDC}}^2}$$

$$I_{\text{priAC}} = 0.2 \text{ A}$$

Output capacitor calculation

$$V_{\text{ripple}} := V_{\text{out}} \cdot 1.5\%$$

$$R_{\text{ESR}} := \frac{V_{\text{ripple}}}{I_{\text{ps}}}$$

$$R_{\text{ESR}} = 0.033 \cdot \Omega$$

$$I_{CoutRMS} := \sqrt{I_{sRMS}^2 - I_{out}^2}$$

$$I_{CoutRMS} = 2.388 \text{ A}$$

Enter Output capacitor selection:

Nichicon LF PLF1C471MDO1, 16 V, 470 μ F Resr = 9 mOhm, Irms = 5.0 A

$$n_{brCout} := 2$$

$$I_{Cout} := n_{brCout} \cdot 5 \text{ A} = 10 \text{ A}$$

$$C_{out} := n_{brCout} \cdot 470 \cdot \mu\text{F} = 940 \cdot \mu\text{F}$$

$$R_{ESR} := \frac{5}{n_{brCout}} \cdot 10^{-3} \cdot \Omega = 2.5 \times 10^{-3} \Omega$$

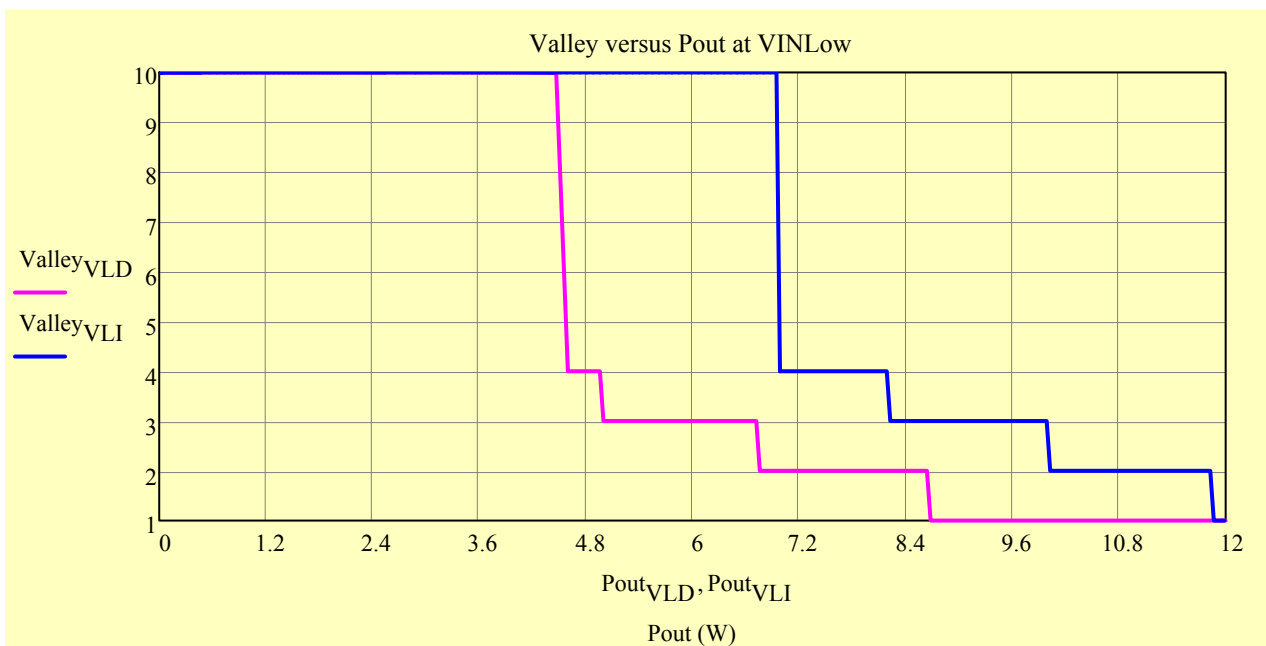
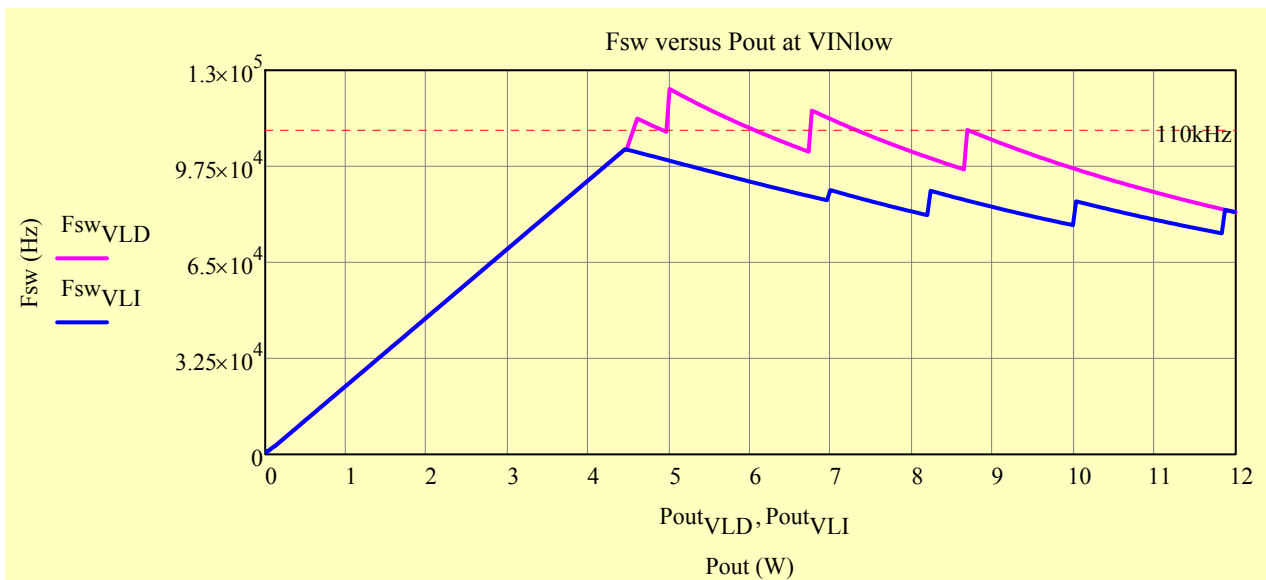


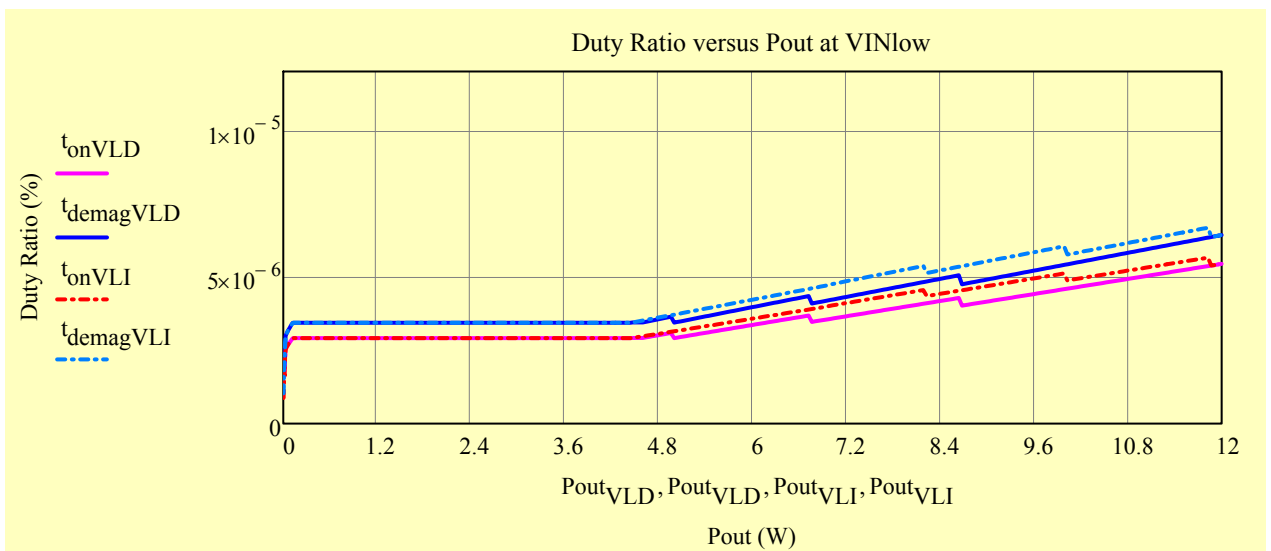
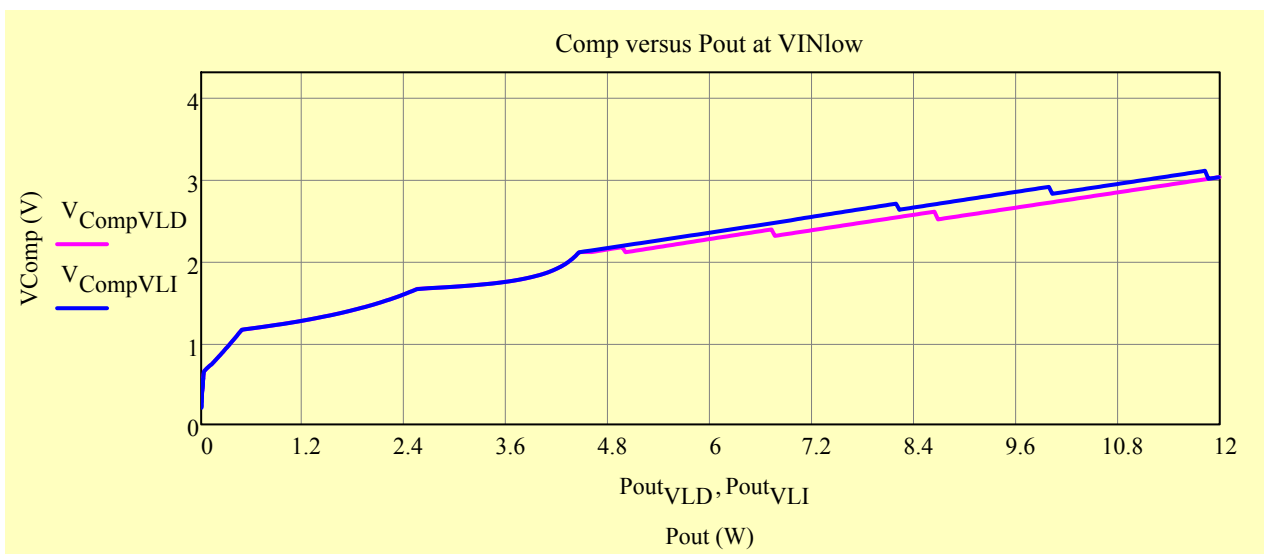
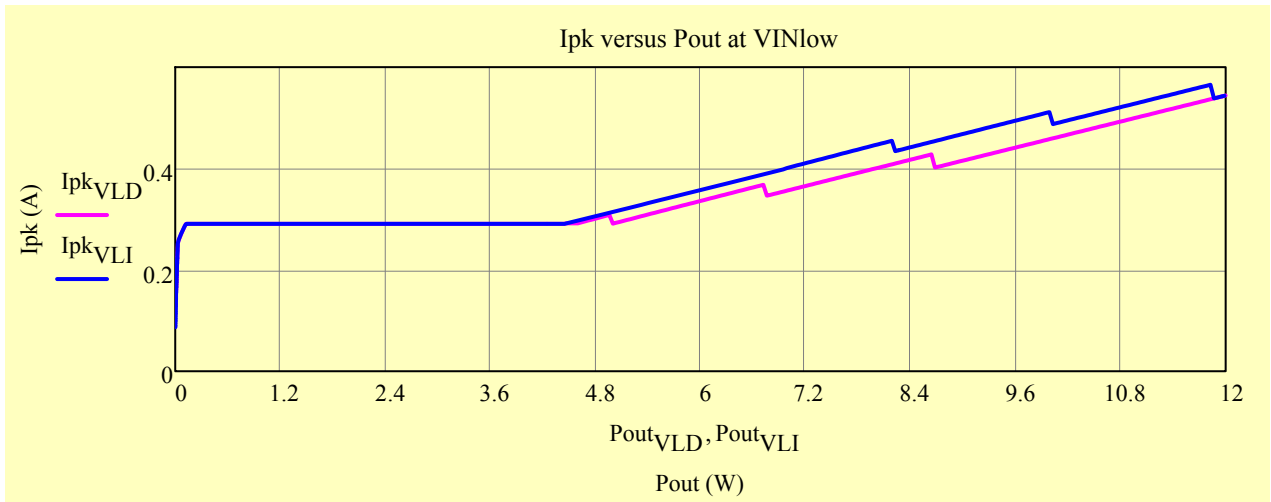
Predicting the evolution of the switching frequency

Enter below the DC input voltage at which you want to see the frequency evolution (these voltages will also be used for the losses calculations)

$$VIN_{low} \equiv 120 \text{ V}$$

$$VIN_{high} \equiv 375 \text{ V}$$





RCD clamp calculation

$$V_{clamp} = 200 \text{ V}$$

Leakage inductance considered for the RCD clamp calculation:

$$k_{\text{leak}} = 1.8\%$$

$$L_{\text{leak}} := L_p \cdot k_{\text{leak}}$$

$$L_{\text{leak}} = 21.6 \mu\text{H}$$

$$R_{\text{clp}} := \frac{2 \cdot V_{\text{clamp}} \cdot \left[V_{\text{clamp}} - \frac{(V_{\text{out}} + V_f)}{N_{\text{ps}}} \right]}{I_{\text{pk}}^2 \cdot L_{\text{leak}} \cdot F_{\text{sw}}}$$

$$R_{\text{clp}} = 77.434 \text{ k}\Omega$$

Enter R_{clp} selection:

$$R_{\text{clp}} := 136 \text{ k}\Omega$$

Enter Voltage Ripple Percentage on Vclamp:

$$\text{Clamp}_{\text{pkpk}} := 50\%$$

$$C_{\text{clp}} := \frac{V_{\text{clamp}}}{R_{\text{clp}} \cdot F_{\text{sw}} \cdot \text{Clamp}_{\text{pkpk}} \cdot V_{\text{clamp}}}$$

$$C_{\text{clp}} = 0.294 \text{ nF}$$

Peak Inverse Voltage of the clamp diode:

$$\text{PIV}_{\text{Dclp}} := \frac{(V_{\text{out}} + V_f)}{N_{\text{ps}}} + V_{\text{os}}$$

$$\text{PIV}_{\text{Dclp}} = 111.613 \text{ V}$$

RCD clamp losses:

$$P_{\text{Clp}} := \frac{V_{\text{clamp}}^2}{R_{\text{clp}}}$$

$$P_{\text{Clp}} = 0.294 \text{ W}$$

Losses calculation: @ Low line input Voltage

Extracted max peak current @ low line from the curves

$$I_{\text{pk_low}} := \max(I_{\text{pkVLD}}, I_{\text{pkVLI}})$$

$$I_{\text{pk_low}} = 0.565 \text{ A}$$

Extracted switching frequency @ the max peak current point from the curves:

$$F_{\text{sw_low}} := \begin{cases} F_{\text{swVLD}_0} & \text{if } I_{\text{pk_low}} = I_{\text{pkVLD}_0} \\ F_{\text{swVLI}_{\text{last}}}(F_{\text{swVLI}}) & \text{otherwise} \end{cases}$$

$$F_{\text{sw_low}} = 82.004 \text{ kHz}$$

Duty Ratio calculations:

$$\text{DR}_{\text{low}} := \frac{I_{\text{pk_low}} \cdot L_p}{V_{\text{IN}_{\text{min}}}} \cdot F_{\text{sw_low}}$$

$$\text{DR}_{\text{low}} = 0.463$$

Transformer primary RMS current:

$$I_{\text{PRMS_low}} := I_{\text{pk_low}} \cdot \sqrt{\frac{\text{DR}_{\text{low}}}{3}}$$

$$I_{\text{PRMS_low}} = 0.222 \text{ A}$$

Transformer secondary RMS current:

$$I_{sRMS_low} := \frac{I_{pk_low}}{N_{ps}} \cdot \sqrt{\frac{1}{3} \cdot (1 - DR_{low})}$$

$$I_{sRMS_low} = 1.927 \text{ A}$$

Output Capacitor RMS current:

$$I_{CoutRMS_low} := \sqrt{I_{sRMS_low}^2 - I_{out}^2}$$

$$I_{CoutRMS_low} = 1.647 \text{ A}$$

Power loss in RCD clamp

$$P_{Clp} = 0.294 \text{ W}$$

Power loss in sense resistor:

$$P_{sense} := R_{sense} \cdot I_{pRMS_low}^2$$

$$P_{sense} = 0.045 \text{ W}$$

Power loss in Cout

$$P_{Cout} := R_{ESR} \cdot I_{CoutRMS_low}^2$$

$$P_{Cout} = 6.783 \times 10^{-3} \text{ W}$$

* Power loss in MOSFET

Drain source resistance at $T_j = 110^\circ\text{C}$:

$$R_{dson110} = 1 \Omega$$

MOSFET C_{OSS} at $V_{ds} = V_0$:

$$C_{OSS} = 10 \cdot \text{pF}$$

Conduction losses:

$$P_{COND}(I_{pRMS}) := I_{pRMS}^2 R_{dson110}$$

Switching losses

Switching losses due to the Power Mosfet only:

$$P_{SW1}(V_{IN_DC}, F_{sw}) := \frac{2}{3} \cdot \left(V_{IN_DC} - \frac{V_{out} + V_f}{N_{ps}} \right)^{\frac{3}{2}} \cdot C_{OSS} \cdot \sqrt{V_0} \cdot F_{sw}$$

Switching losses due to the extra capacitor that it could be placed in parallel with the Power Mosfet:

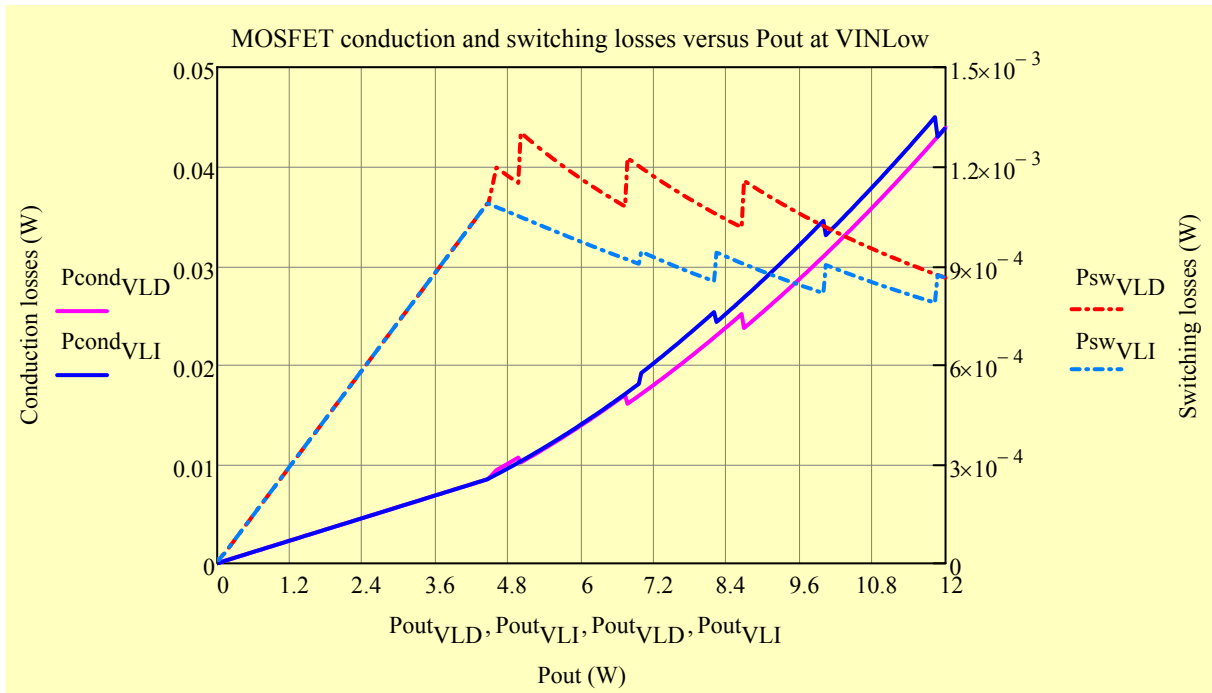
$$P_{SW2}(V_{IN_DC}, F_{sw}) := \frac{1}{2} \cdot C_{DS} \cdot \left(V_{IN_DC} - \frac{V_{out} + V_f}{N_{ps}} \right)^2 \cdot F_{sw}$$

Switching total losses is the sum:

$$P_{SW}(V_{IN_DC}, F_{sw}) := P_{SW1}(V_{IN_DC}, F_{sw}) + P_{SW2}(V_{IN_DC}, F_{sw})$$

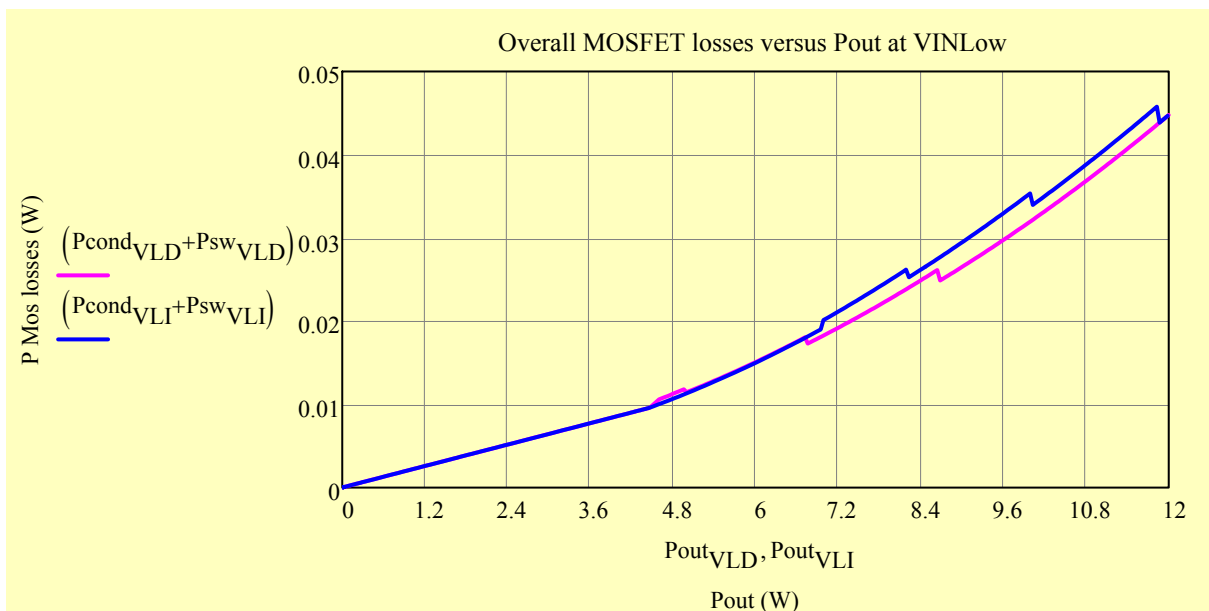
Due to the QR mode and thanks to the power mosfet losses graph it is possible to extract the worst case conditions losses:

$$VIN_{low} = 120 \text{ V}$$



The following graph illustrates the sum of the switching losses and conduction losses versus the output power and at different input voltages:

$$VIN_{low} = 120 \text{ V}$$



Thus worst case mosfet losses is extracted from the graphs above:

$$VIN_{low} = 120 \text{ V}$$

$$VIN_{high} = 375 \text{ V}$$

$$P_{MOS} := \max(P_{condVLD} + P_{swVLD}, P_{condVLI} + P_{swVLI}, P_{condVHD} + P_{swVHD}, P_{condVHI} + P_{swVHI})$$

$$P_{MOS} = 0.099 \text{ W}$$

* **Power loss in output diode**

Peak inverse voltage :

$$PIV_{diode} := VIN_{max} \cdot Nps + V_{out} + V_f$$

$$PIV_{diode} = 59.1 \text{ V}$$

Output diode : **NRVTSS5100E**

Diode forward voltage at low current:

$$V_{f0} = 0.2 \text{ V} \quad @ 125^\circ\text{C}$$

Diode dynamic resistance:

$$R_d := \frac{0.1 \text{ V}}{2 \text{ A}} = 0.05 \Omega$$

$$P_{Diode} := V_{f0} \cdot I_{out} + R_d \cdot I_{SRMS_low}^2$$

$$P_{Diode} = 0.386 \text{ W}$$

* **Power loss in Synchronous Rectification MOSFET if it is used instead of Schottky diode**

Mosfet reference: NTMFS5C612NL from ONSEMI

Drain source resistance at $T_j = 110^\circ\text{C}$:

$$R_{SRdson110} := 0.00345 \Omega$$

MOSFET C_{OSS} at $V_{ds} = V_{SR_o}$:

$$C_{SR_OSS} := 2953 \text{ pF}$$

$$V_{SR_o} := 25 \text{ V}$$

Maximum forward body diode:

$$V_{SR_SD} := 0.66 \text{ V}$$

Estimated maximum duration of the body diode conduction:

$$t_{BD_on} := 100 \text{ ns}$$

Conduction losses:

$$I_{pk} := I_{pkVLD} \quad t_{demag} := t_{demagVLD} \quad F_{sw} := F_{swVLD}$$

$$P_{SR_condVLD} := \left[\left[\frac{I_{pk}}{Nps} \cdot \sqrt{\frac{1}{3} \cdot (t_{demag} \cdot F_{sw})} \right]^2 R_{SRdson110} \right]$$

$$I_{pk} := I_{pkVLI} \quad t_{demag} := t_{demagVLI} \quad F_{sw} := F_{swVLI}$$

$$P_{SR_condVLI} := \left[\left[\frac{I_{pk}}{Nps} \cdot \sqrt{\frac{1}{3} \cdot (t_{demag} \cdot F_{sw})} \right]^2 R_{SRdson110} \right]$$

$$I_{pk} := I_{pkVHD} \quad t_{demag} := t_{demagVHD} \quad F_{sw} := F_{swVHD}$$

$$P_{SR_condVHD} := \left[\left[\frac{I_{pk}}{Nps} \cdot \sqrt{\frac{1}{3} \cdot (t_{demag} \cdot F_{sw})} \right]^2 R_{SRdson110} \right]$$

$$\overset{msw}{I_{pk}} := I_{pkVHI} \quad \overset{demag}{t_{demag}} := t_{demagVHI} \quad \overset{msw}{F_{sw}} := F_{swVHI}$$

$$P_{SR_condVHI} := \left[\frac{I_{pk}}{N_{ps}} \cdot \sqrt{\frac{1}{3} \cdot \left[\overset{msw}{t_{demag}} \cdot \overset{msw}{F_{sw}} \right]} \right]^2 R_{SRdson110}$$

Switching losses

Thanks to the body diode of the sync power mosfet, the SR mosfet is turned on at almost null voltage ($V_f \sim 1.0 \text{ V}$), thus the switching losses could be neglected. However we could consider the losses due to the body diode conduction before the power mosfet is turned on.

Body diode losses :

$$\overset{msw}{I_{pk}} := I_{pkVLD} \quad \overset{msw}{F_{sw}} := F_{swVLD}$$

$$P_{SR_SDVLD} := \left(V_{SR_SD} \cdot \frac{I_{pk}}{N_{ps}} \cdot t_{BD_on} \cdot F_{sw} \right)$$

$$\overset{msw}{I_{pk}} := I_{pkVLI} \quad \overset{msw}{F_{sw}} := F_{swVLI}$$

$$P_{SR_SDVLI} := \left(V_{SR_SD} \cdot \frac{I_{pk}}{N_{ps}} \cdot t_{BD_on} \cdot F_{sw} \right)$$

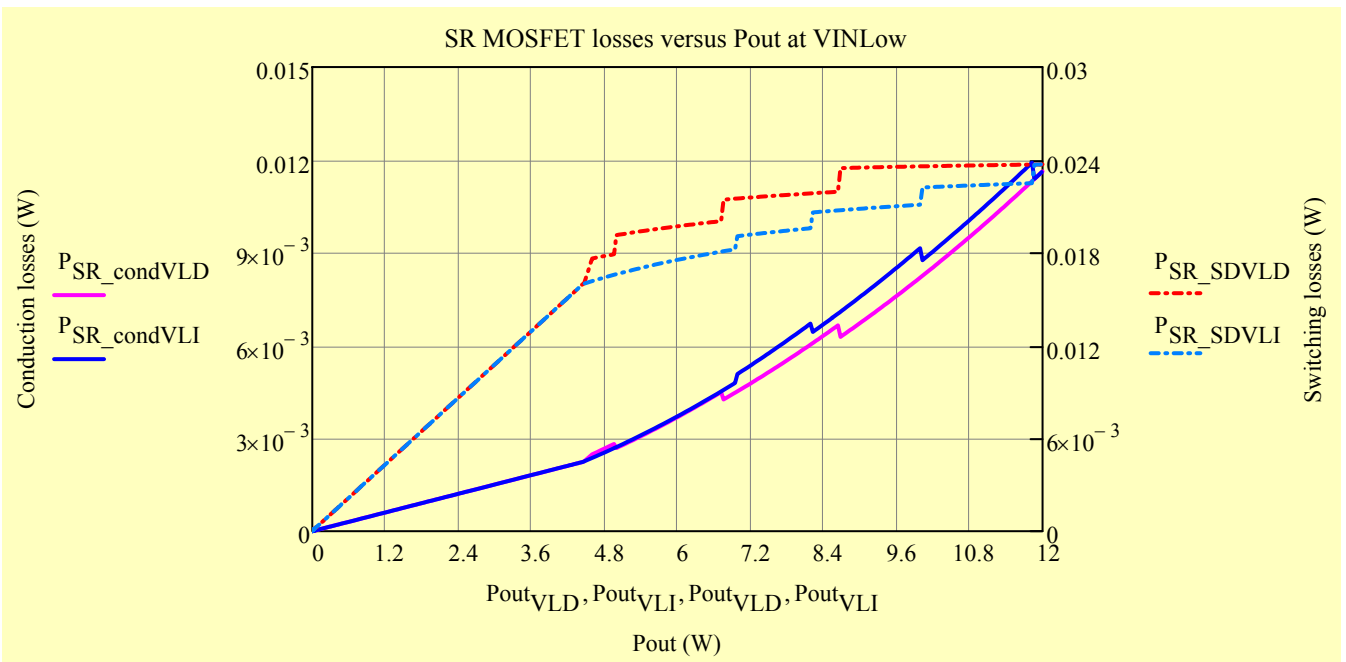
$$\overset{msw}{I_{pk}} := I_{pkVHD} \quad \overset{msw}{F_{sw}} := F_{swVHD}$$

$$P_{SR_SDVHD} := \left(V_{SR_SD} \cdot \frac{I_{pk}}{N_{ps}} \cdot t_{BD_on} \cdot F_{sw} \right)$$

$$\overset{msw}{I_{pk}} := I_{pkVHI} \quad \overset{msw}{F_{sw}} := F_{swVHI}$$

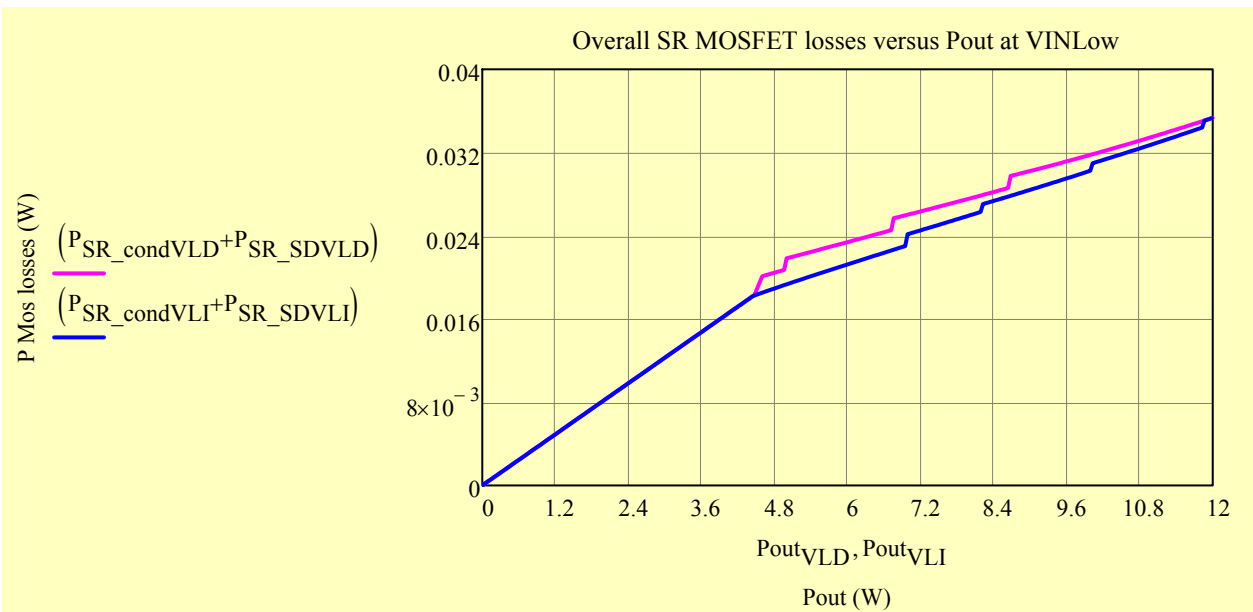
$$P_{SR_SDVHI} := \left(V_{SR_SD} \cdot \frac{I_{pk}}{N_{ps}} \cdot t_{BD_on} \cdot F_{sw} \right)$$

$$V_{IN_{low}} = 120 \text{ V}$$



The following graph illustrates the sum of the switching losses and conduction losses versus the output power and at different input voltages:

$$VIN_{low} = 120 \text{ V}$$



Thus worst case SR mosfet losses is extracted from the graphs above:

$$P_{SR_MOS} := \max(P_{SR_condVLD} + P_{SR_SDVLD}, P_{SR_condVLI} + P_{SR_SDVLI}, P_{SR_condVHD} + P_{SR_SDVHD}, P_{SR_co})$$

$$P_{SR_MOS} = 0.042 \text{ W}$$

*** Compensating the power supply**

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

$$H_0(V_{\text{INDC}}) := \frac{R_{\text{load}}}{2 \cdot K_{\text{comp}} C_V \cdot N_{\text{ps}} \cdot R_{\text{sense}} \cdot \left(2 \cdot \frac{V_{\text{out}}}{N_{\text{ps}} \cdot V_{\text{INDC}}} + 1 \right)}$$

$$H_0(120\text{V}) = 5.104$$

$$s_{z1} := \frac{1}{R_{\text{ESR}} \cdot C_{\text{out}}}$$

$$s_{z2}(V_{\text{INDC}}) := \frac{R_{\text{load}}}{N_{\text{ps}}^2 \cdot L_p} \cdot \frac{1}{\frac{V_{\text{out}}}{N_{\text{ps}} \cdot V_{\text{INDC}}} \cdot \left(1 + \frac{V_{\text{out}}}{N_{\text{ps}} \cdot V_{\text{INDC}}} \right)}$$

$$s_{p1}(V_{\text{INDC}}) := \frac{1}{R_{\text{load}} \cdot C_{\text{out}}} \cdot \frac{2 \cdot \frac{V_{\text{out}}}{N_{\text{ps}} \cdot V_{\text{INDC}}} + 1}{\frac{V_{\text{out}}}{N_{\text{ps}} \cdot V_{\text{INDC}}} + 1}$$

Power stage without ZOH:

$$H_1(s, V_{\text{INDC}}) := H_0(V_{\text{INDC}}) \cdot \frac{\left(1 + \frac{s}{s_{z1}} \right) \cdot \left(1 - \frac{s}{s_{z2}(V_{\text{INDC}})} \right)}{\left(1 + \frac{s}{s_{p1}(V_{\text{INDC}})} \right)}$$

Transformer Gain:

$$K_{T0} := \frac{N_{\text{aux}}}{N_{\text{ps}}} = 0.718 \quad 20 \cdot \log(K_{T0}) = -2.881$$

Power stage on Aux winding without ZOH:

$$H_2(s, V_{\text{INDC}}) := H_1(s, V_{\text{INDC}}) \cdot K_{T0}$$

Power Stage with ZOH:

End of Demagnetization Transfer function:

$$K_{D0} := \frac{R_{\text{lower}}}{R_{\text{lower}} + R_{\text{upper}}} = 0.31641$$

$$\tau_1 := \frac{R_{\text{lower}} \cdot R_{\text{upper}}}{R_{\text{lower}} + R_{\text{upper}}} \cdot C_{ZCD} = 29.394 \cdot \text{ns}$$

$$K_D(s) := K_{D0} \cdot \frac{1}{1 + s \cdot 2 \cdot \pi \cdot \tau_1}$$

Internal Sample & Hold (ZOH):

ZOH Transfer function:

$$T_{ZOH}(s, T) := \frac{1 - e^{-s \cdot T}}{s \cdot T}$$

Switching frequency @ full load versus min and max input voltage:

$$T_{\text{swZOH}} := \begin{pmatrix} F_{\text{swVLD}_0} \\ F_{\text{swVHD}_0} \end{pmatrix} = \begin{pmatrix} 81.922 \\ 125.836 \end{pmatrix} \cdot \text{kHz}$$

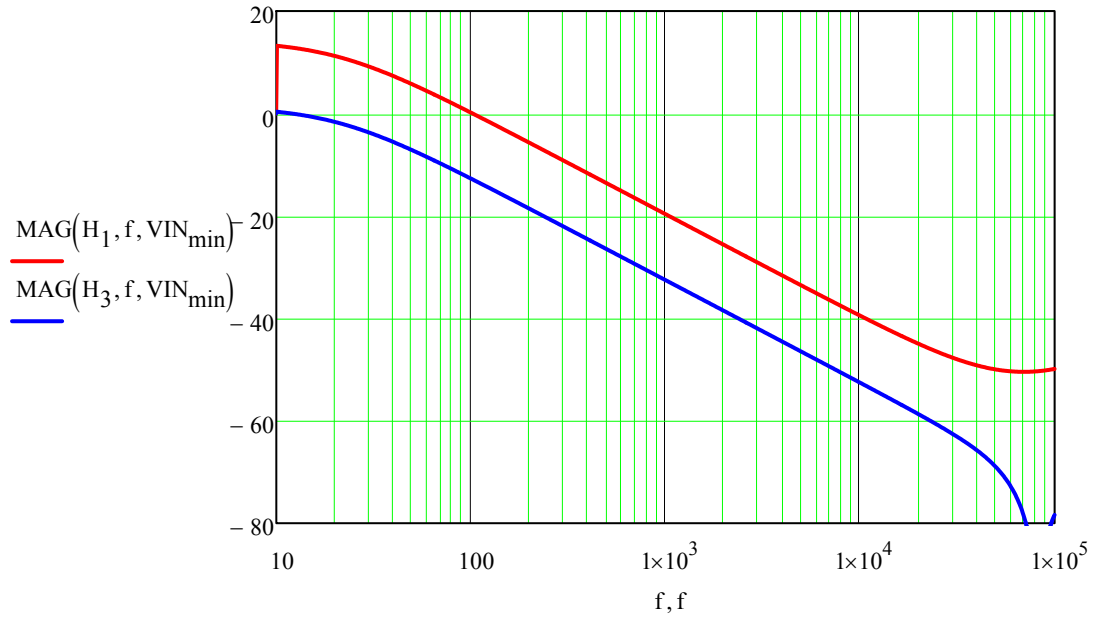
G3 Power Stage integrating internal transfer function (Demag detection & ZOH):

$$H_3(s, V_{\text{IN}_{\text{DC}}}) := \begin{cases} T \leftarrow \frac{1}{T_{\text{swZOH}_0}} & \text{if } V_{\text{IN}_{\text{DC}}} = V_{\text{IN}_{\text{min}}} \\ T \leftarrow \frac{1}{T_{\text{swZOH}_1}} & \text{otherwise} \\ H_2(s, V_{\text{IN}_{\text{DC}}}) \cdot K_D(s) \cdot T_{ZOH}(s, T) \end{cases}$$

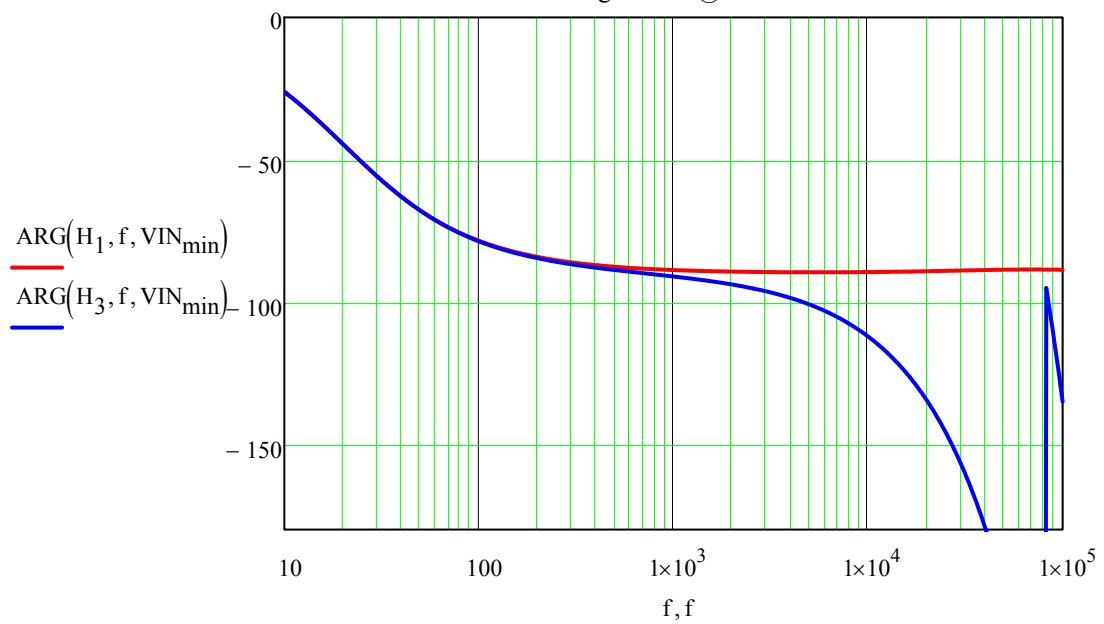
Tools for Bode Plot:



Power Stage Gain @ VINminDC



Power Stage Phase @ VINminDC



Type 2 OTA with automated calculations

$$R_0 := \frac{1}{g_m} = 5 \cdot \text{k}\Omega$$

Selected Crossover frequency (Fc) and the wanted Phase Margin (PM):

$$F_c := 1 \text{ kHz} \quad \text{PM} := 70^\circ$$

Power stage Gain and Phase at the selected crossover frequency (including end of demag detection and ZOH):

$$G_{F_c} := 20 \cdot \log\left(\left|H_3(i \cdot 2 \cdot \pi \cdot F_c, \text{VIN}_{\min})\right|\right)$$

$$G_{F_c} = -32.523$$

$$P_{F_c} := \arg\left(H_3(i \cdot 2 \cdot \pi \cdot F_c, \text{VIN}_{\min})\right)$$

$$P_{F_c} = -91.055^\circ$$

$$\text{Boost} := \text{PM} - P_{F_c} - 90^\circ$$

$$\text{Boost} = 71.055^\circ$$

$$G_0 := 10^{\left(\frac{-G_{F_c}}{20}\right)}$$

$$G_0 = 42.281$$

$$k_1 := \tan\left(\frac{\text{Boost}}{2} + 45^\circ\right)$$

$$k_1 = 5.993$$

$$F_z := \frac{F_c}{k_1}$$

$$F_z = 166.85 \cdot \text{Hz}$$

$$F_p := k_1 \cdot F_c$$

$$F_p = 5.993 \cdot \text{kHz}$$

$$R_2 := \frac{G_0}{g_m}$$

$$R_2 = 211.404 \cdot \text{k}\Omega$$

$$C_2 := \frac{1}{2\pi R_2 F_z}$$

$$C_2 = 4.512 \cdot \text{nF}$$

$$C_1 := \frac{1}{2\pi R_2 F_p}$$

$$C_1 = 0.126 \cdot \text{nF}$$

$$G_0 := g_m \cdot \frac{R_2 \cdot C_2}{C_1 + C_2} \quad G_1(s) := -G_0 \cdot \frac{1 + \frac{2 \cdot \pi \cdot F_z}{s}}{1 + \frac{s}{2 \cdot \pi \cdot F_p}}$$

$$\text{PM1} := \arg\left(G_1(i \cdot 2 \cdot \pi \cdot F_c)\right) + P_{F_c}$$

$$\text{PM1} = 70^\circ$$

$$F_{p0}(R_0, C_1, C_2) := \frac{1}{2 \cdot \pi \cdot R_0 \cdot (C_1 + C_2)}$$

$$F_{p1}(R_2, C_1, C_2) := \frac{1}{2 \cdot \pi \cdot R_2 \cdot \frac{C_1 \cdot C_2}{C_1 + C_2}}$$

$$F_z(R_2, C_2) := \frac{1}{2 \cdot \pi \cdot R_2 \cdot C_2}$$

$$F_c(R_2, C_1, C_2) := \sqrt{F_z(R_2, C_2) \cdot F_{p1}(R_2, C_1, C_2)}$$

Normalized value

$$R_2 := 220 \text{ k}\Omega$$

$$C_2 := 4.7 \text{ nF}$$

$$C_1 := 120 \text{ pF}$$

$$F_{p0}(R_0, C_1, C_2) = 6.604 \times 10^3 \cdot \text{Hz}$$

$$F_{p1}(R_2, C_1, C_2) = 6.183 \cdot \text{kHz}$$

$$F_z(R_2, C_2) = 153.922 \cdot \text{Hz}$$

$$F_c(R_2, C_1, C_2) = 975.512 \cdot \text{Hz}$$

$$G_{01} := g_m \cdot \frac{R_2 \cdot C_2}{C_1 + C_2}$$

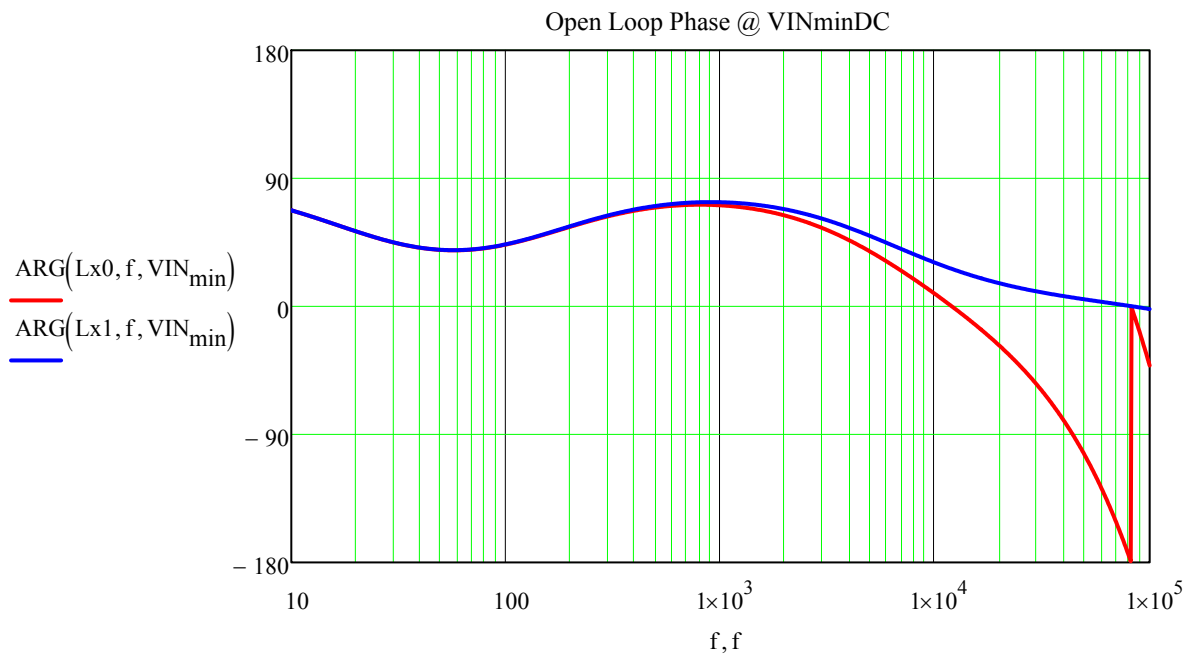
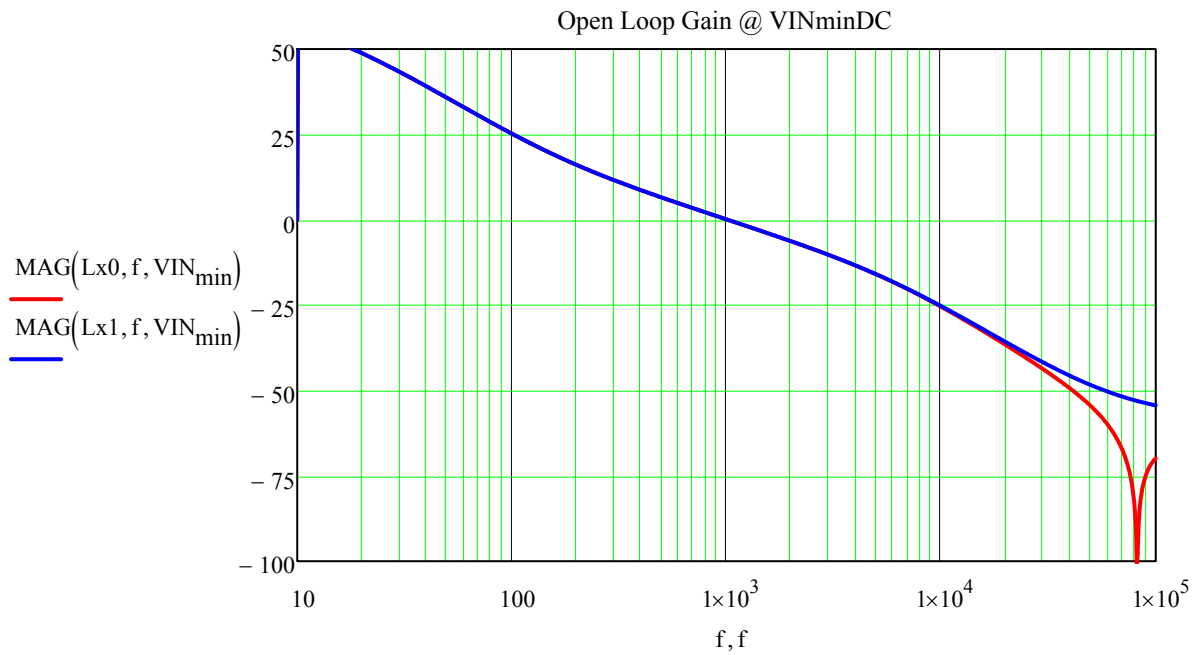
$$G_{11}(s) := -G_{01} \cdot \frac{1 + \frac{2 \cdot \pi \cdot F_z(R_2, C_2)}{s}}{1 + \frac{s}{2 \cdot \pi \cdot F_{p1}(R_2, C_1, C_2)}}$$

Open loop with ZOH:

$$L_{x0}(s, \text{VIN}_{\text{DC}}) := \begin{cases} T \leftarrow \frac{1}{T_{\text{swZOH}_0}} & \text{if } \text{VIN}_{\text{DC}} = \text{VIN}_{\text{min}} \\ T \leftarrow \frac{1}{T_{\text{swZOH}_1}} & \text{otherwise} \end{cases} \cdot H_2(s, \text{VIN}_{\text{DC}}) \cdot G_{11}(s) \cdot K_D(s) \cdot T_{\text{ZOH}}(s, T)$$

Open loop without ZOH:

$$L_{x1}(s, \text{VIN}_{\text{DC}}) := H_2(s, \text{VIN}_{\text{DC}}) \cdot G_{11}(s) \cdot K_D(s)$$



Stability Criteria:

crossover frequency:

$$f_{c0} := f_c(Lx0, VIN_{min}) = 1.013 \cdot \text{kHz}$$

Phase margin:

$$PM_0 := PM(Lx0, VIN_{min}) = 70.957^\circ$$

crossover frequency:

$$f_{c1} := f_c(Lx1, VIN_{min}) = 1.013 \cdot \text{kHz}$$

Frequency @ Phase = 0°

$$f_{g0} := f_g(Lx0, VIN_{min}) = 11.98 \cdot \text{kHz}$$

Gain margin @ 180°:

$$GM_0 := GM(Lx0, VIN_{min}) = -28.263$$

Frequency @ Phase = 0°

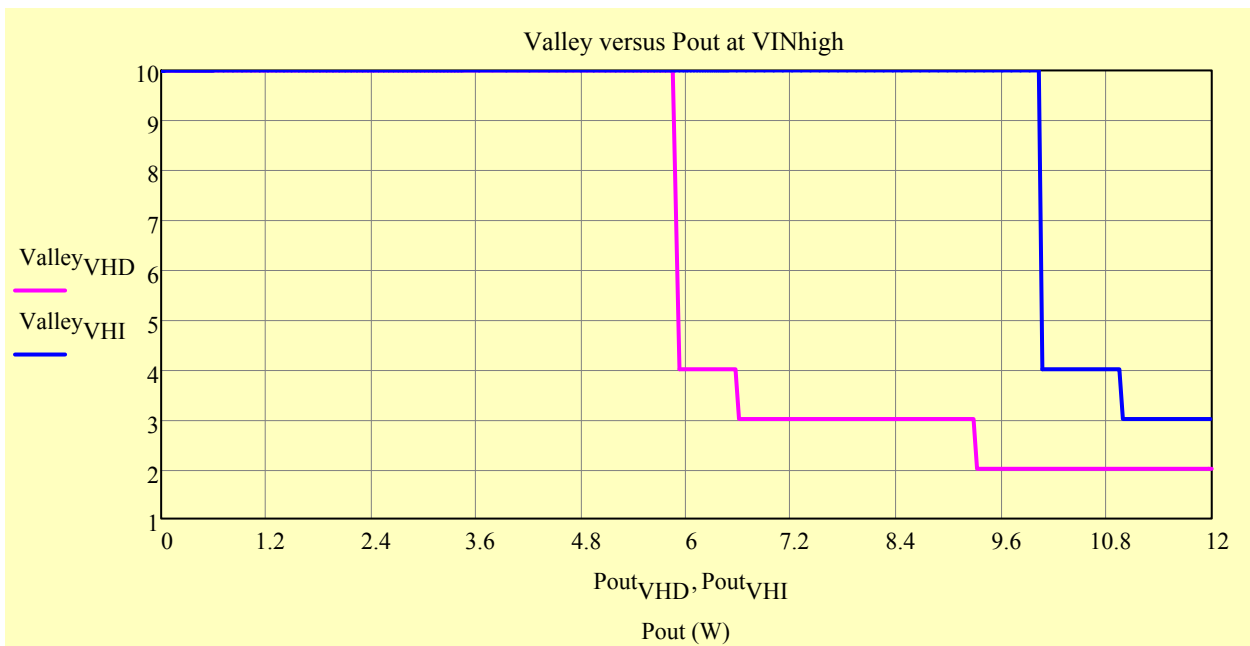
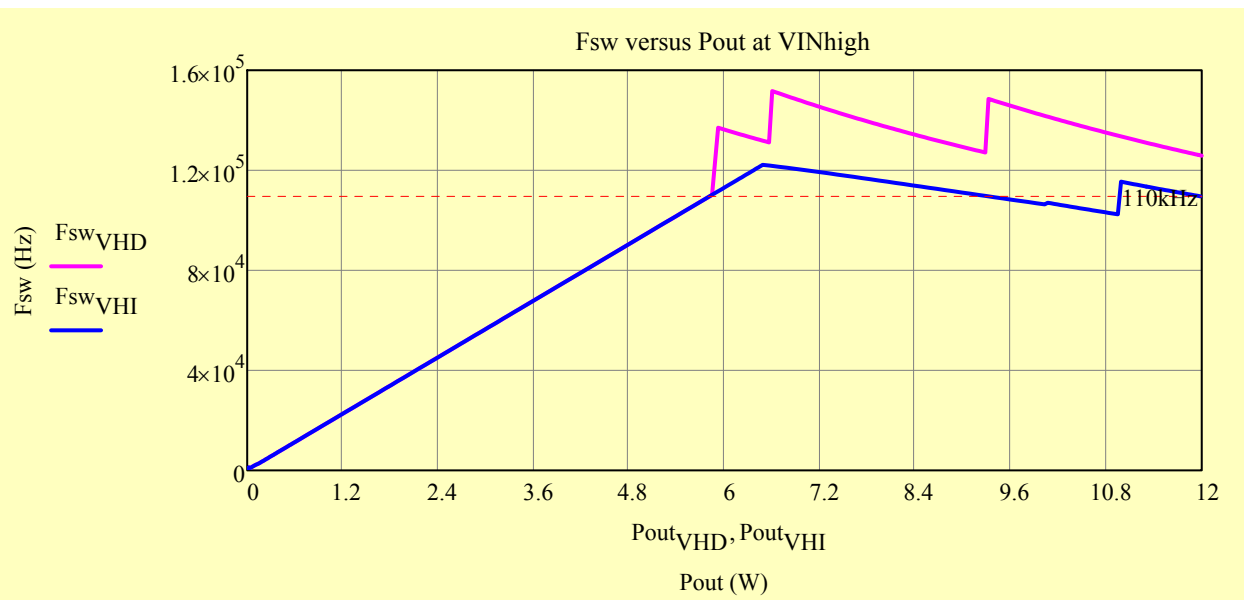
$$f_{g1} := f_g(Lx1, VIN_{min}) = 83.149 \cdot \text{kHz}$$

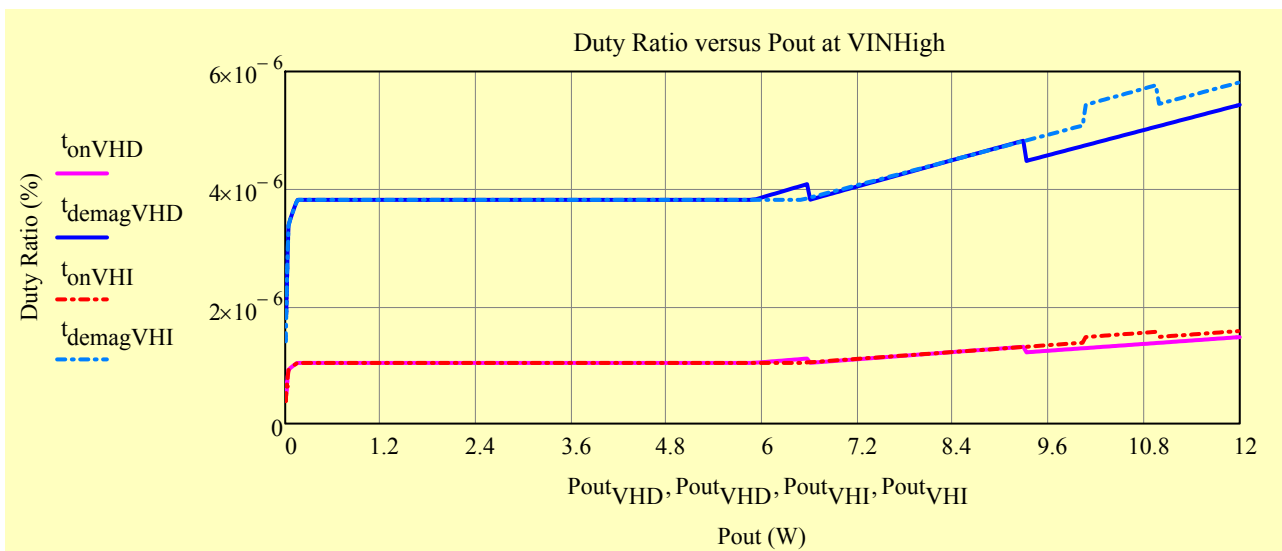
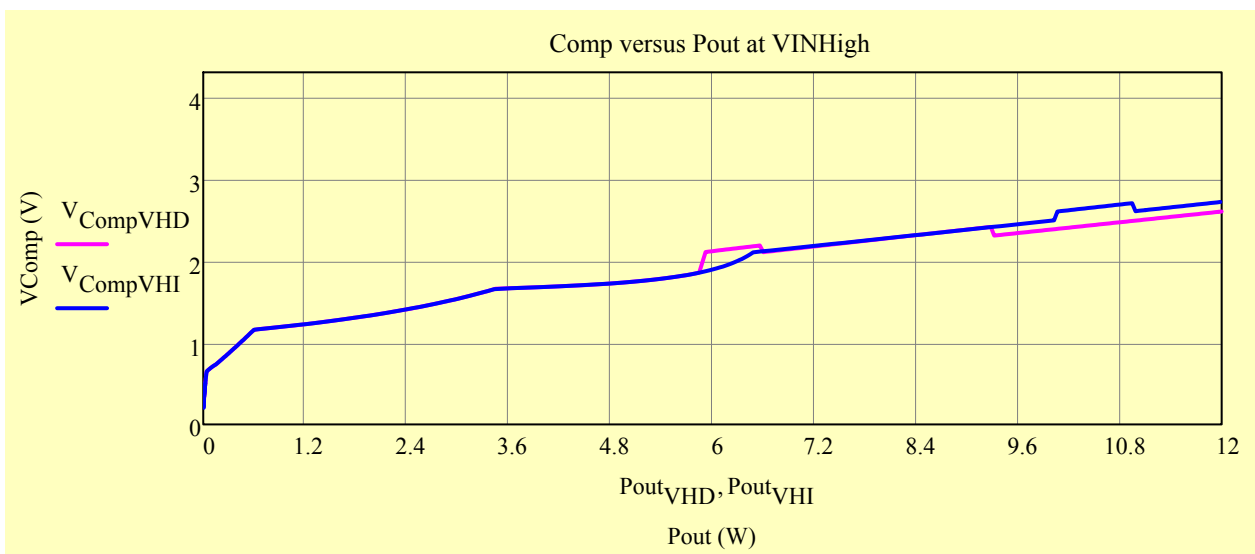
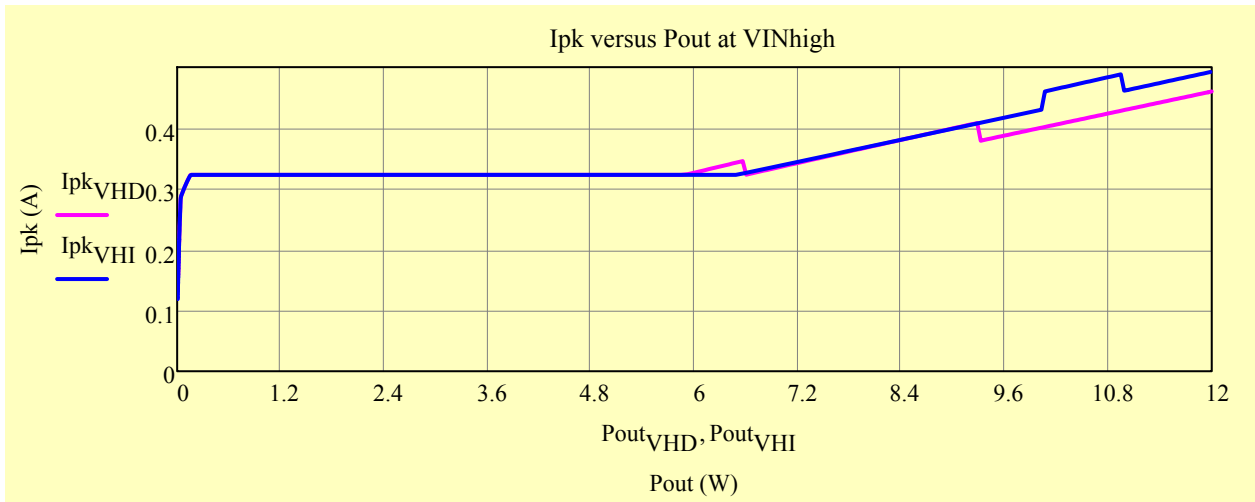
Phase margin:

$$PM_1 := PM(Lx1, VIN_{\min}) = 73.182^\circ$$

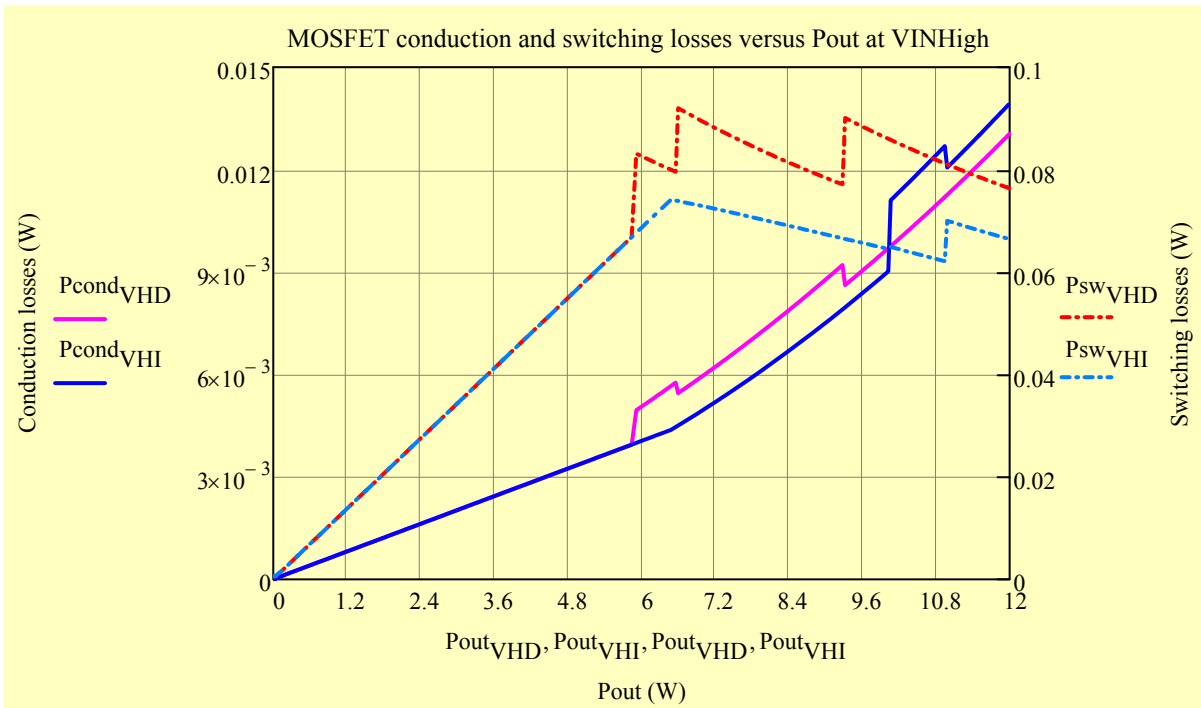
Gain margin @ 180°:

$$GM_1 := GM(Lx1, VIN_{\min}) = -53.167$$

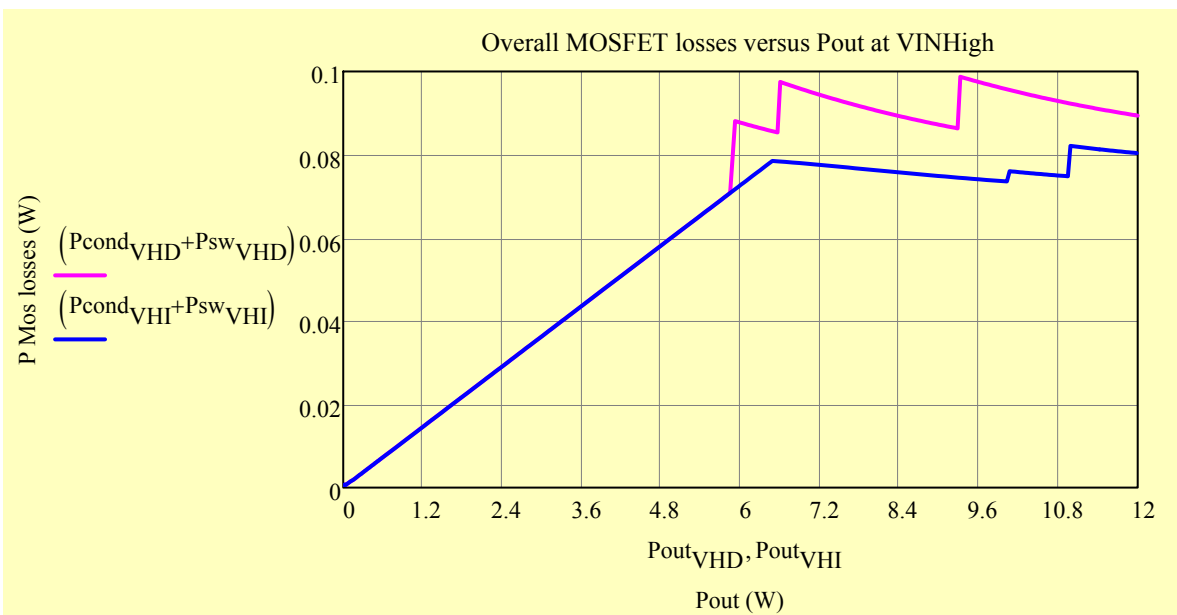




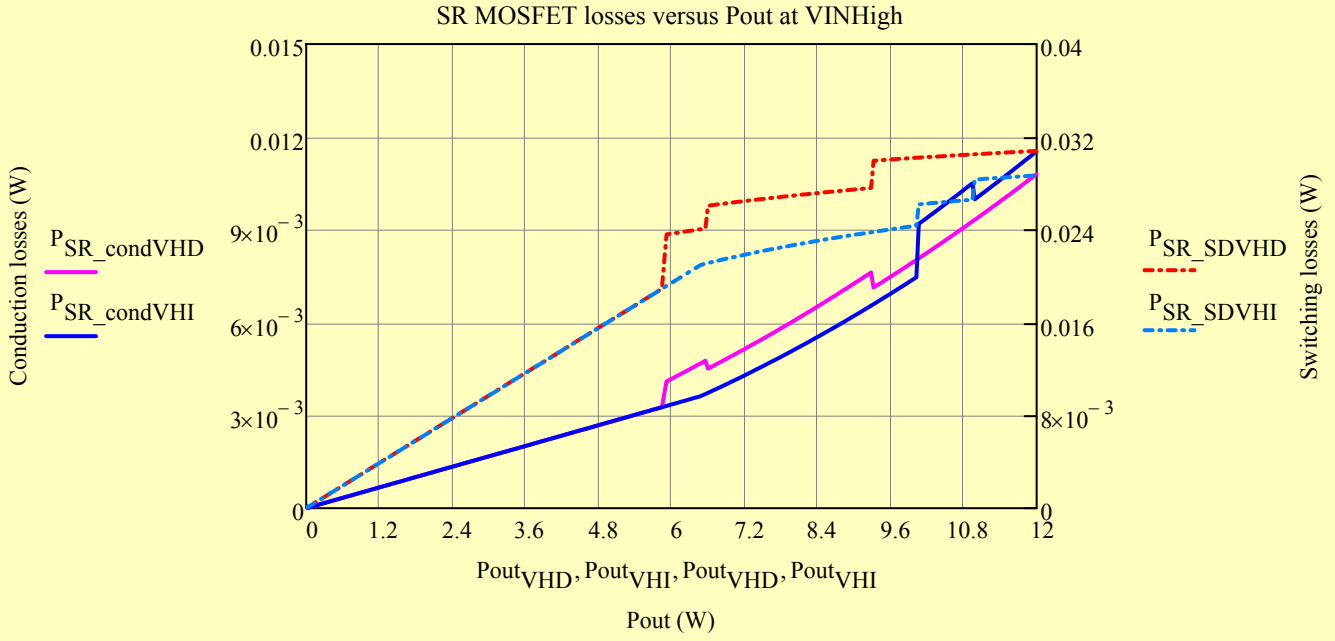
$V_{IN_{high}} = 375 \text{ V}$



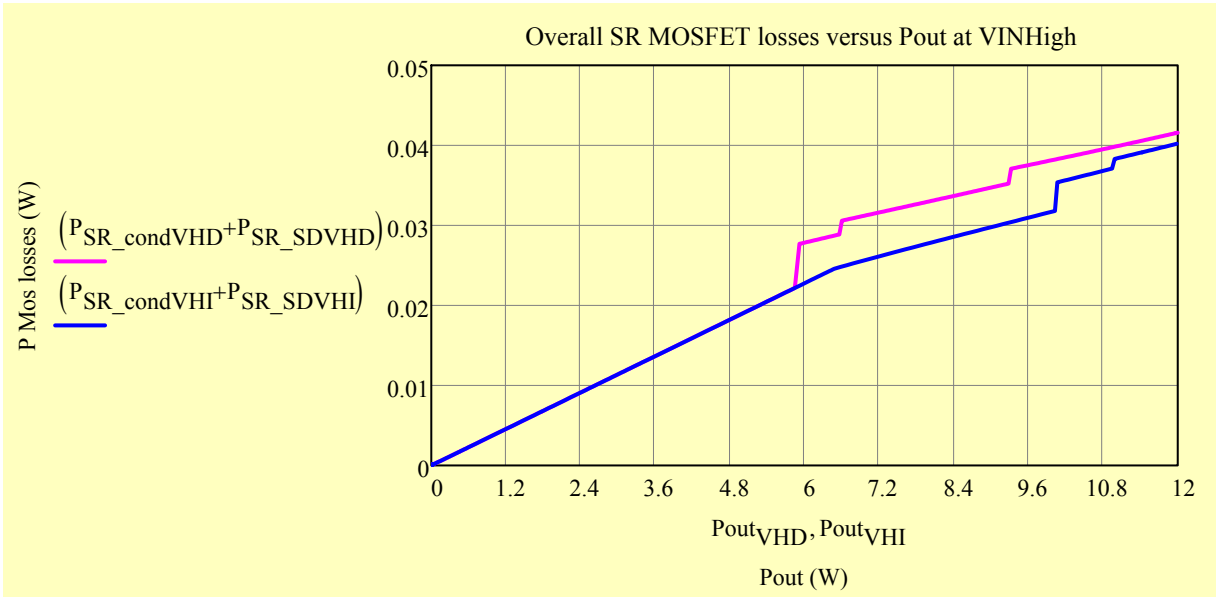
$V_{IN_{high}} = 375 \text{ V}$



$$V_{IN_{high}} = 375 \text{ V}$$

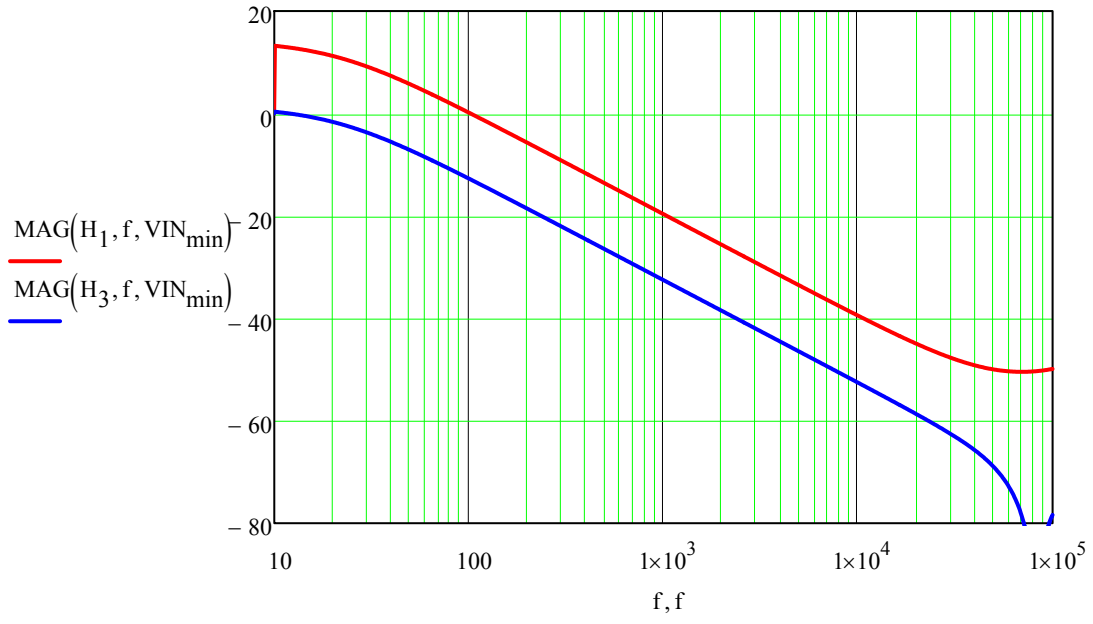


$V_{IN_high} = 375 V$

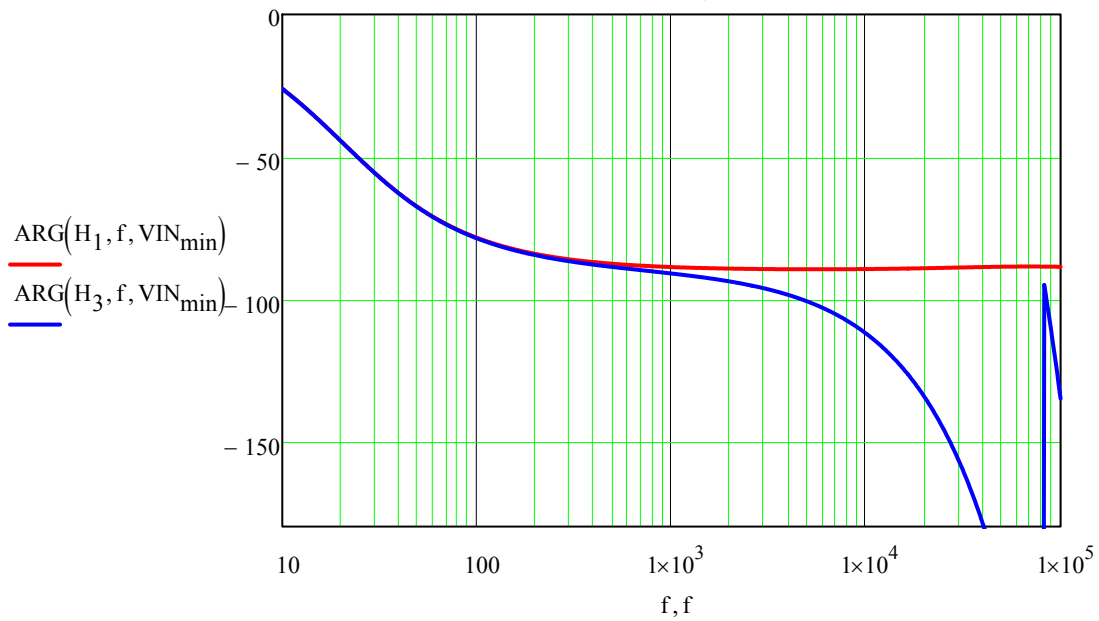


$ndVHI + P_{SR_SDVHI}$

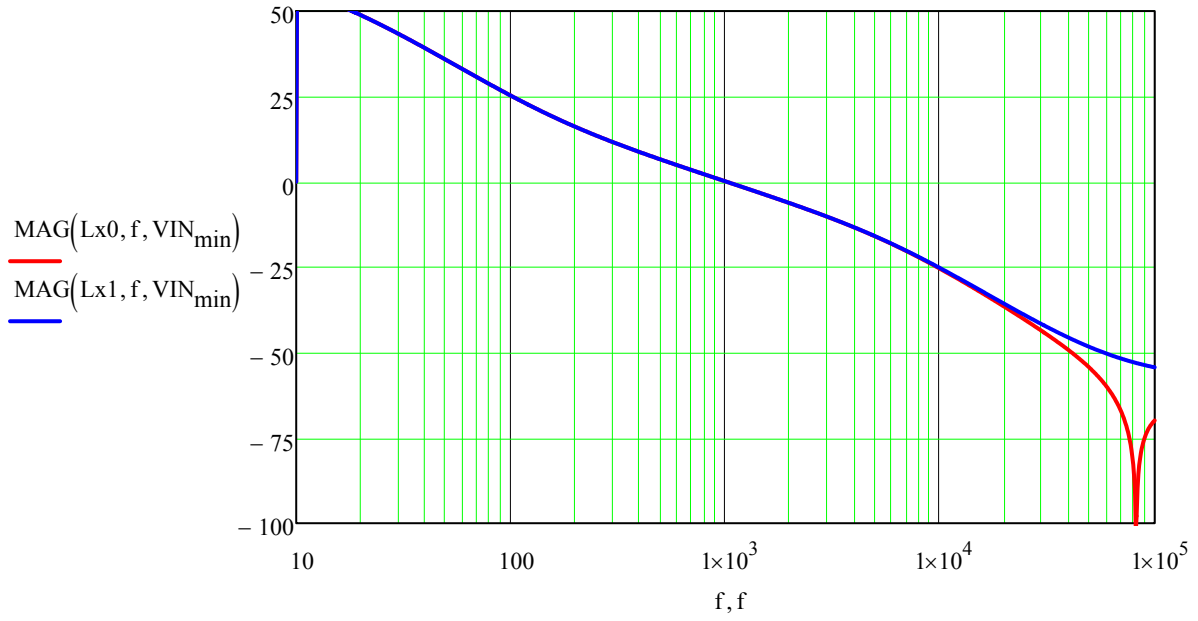
Power Stage Gain @ VINmaxDC



Power Stage Phase @ VINmaxDC



Open Loop Gain @ VINminDC



Open Loop Phase @ VINminDC

