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Avoid Design Problems Using Worst Case Analysis Calculations

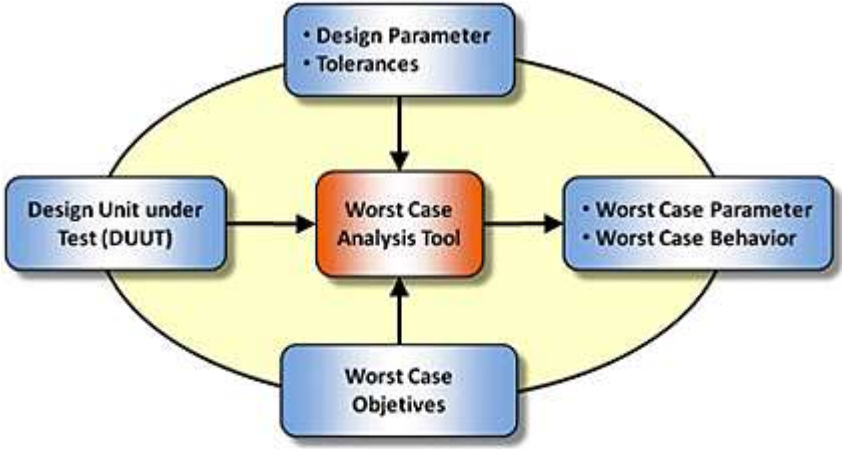
2nd Edition

Agenda

- Discussion on what is worst case analysis
- Different types of worst case analysis – i.e.: Extreme value, RSS
- Discussion on electronic component tolerances – resistors, capacitors, and Inductors, with an inductor saturation example.
- Example 1: Output voltage regulation. Reference and IC tolerance included.
- Example 2: Feedback loop stability WCA.
- Example 3: MOSFET Power dissipation. FET and Diode tolerances included.

Worst Case Analysis Definition

- A worst-case analysis is an assessment of a circuits functional performance, accounting for tolerances, such as **Beginning of life (BOL)**, environmental **(Temperature),** aging **End of Life (EOL)**, and, in the case of Space applications, radiation tolerances.



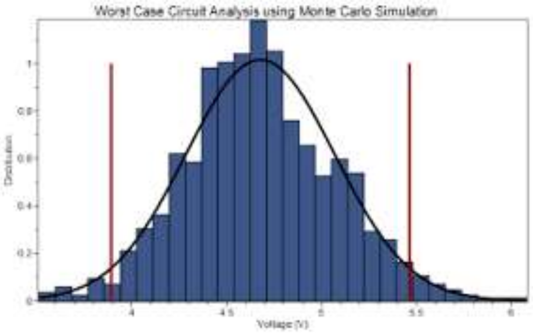
Worst Case Analysis Method Types

- **Extreme Value Analysis (EVA)** This is an estimate of the most extreme limits of the circuit's components and function.

- **Root Sum Square (RSS)** method works on a statistical approach. It assumes that most of the components fall to the mid of the tolerance zone rather than at the extreme ends.

$$\Delta Y = \sqrt{\sum_{i=1}^{n} \delta_i^2}$$

- **Monte Carlo analysis**, in which parameters are randomly selected from a distribution, and the circuit simulated, anywhere from 1000 to 100000 times.



Worst Case Analysis component Tolerances

Resistor Tolerances

EOL obtained from component manufacturer, or engineering APL

$delT := 75$

$tol\_rd1\_bol := 0.1 \cdot \%$	$tol\_rd1\_eol := 0.5 \cdot \%$	$tol\_rd1\_temp := 25 \cdot 10^{-6} \cdot delT$	ppm /C
$tol\_rd2\_bol := 1 \cdot \%$	$tol\_rd2\_eol := 0.5 \cdot \%$	$tol\_rd2\_temp := 100 \cdot 10^{-6} \cdot delT$	ppm /C
$tol\_rd3\_bol := 1 \cdot \%$	$tol\_rd3\_eol := 0.5 \cdot \%$	$tol\_rd3\_temp := 250 \cdot 10^{-6} \cdot delT$	ppm /C
$tol\_rd4\_bol := 10 \cdot \%$	$tol\_rd4\_eol := 0.5 \cdot \%$	$tol\_rd4\_temp := 2000 \cdot 10^{-6} \cdot delT$	ppm /C

Variations

$k1 := (tol\_rd1\_bol + tol\_rd1\_eol + tol\_rd1\_temp)$ $\qquad k1 = 7.875 \cdot 10^{-3}$

$k2 := (tol\_rd2\_bol + tol\_rd2\_eol + tol\_rd2\_temp)$ $\qquad k2 = 0.023$

$xr23 := 53.6 \cdot k$

$xr23min := xr23 \cdot (1 - k1)$

$xr23max := xr23 \cdot (1 + k1)$

$$\boxed{\begin{array}{l} xr23min = 5.318 \cdot 10^{4} \\ xr23max = 5.402 \cdot 10^{4} \end{array}}$$

Worst Case Analysis component Tolerances

Capacitor Tolerances

EOL obtained from component manufacturer, or engineering APL

$delT := 75$

$tol\_npo\_bol := 5 \cdot \%$

$tol\_bx\_bol := 10 \cdot \%$

$tol\_x7r\_bol := 10 \cdot \%$

$tol\_npo\_eol := 0.5 \cdot \%$

$tol\_bx\_eol := 21 \cdot \%$

$tol\_x7r\_eol := 21 \cdot \%$

$tol\_npo\_temp := 30 \cdot 10^{-6} \cdot delT$

$tol\_bx\_temp := 15 \cdot \%$

$tol\_x7r\_temp := 15 \cdot \%$

BX characteristics are identical to X7R dielectric, with the added restriction that the Temperature-Voltage Coefficient (TVC) is not to exceed -25% ΔC at rated voltage, over the operating temperature range (-55°C to 125°C).

Variations

$k3 := (tol\_npo\_bol + tol\_npo\_eol + tol\_npo\_temp)$ $\quad k3 = 0.057$

$k4 := (tol\_bx\_bol + tol\_bx\_eol + tol\_bx\_temp)$ $\quad k4 = 0.46$

$k5 := (tol\_x7r\_bol + tol\_x7r\_eol + tol\_x7r\_temp)$ $\quad k5 = 0.46$

$a1c12 := 39 \cdot p$

$a1c12min := a1c12 \cdot (1 - k3)$

$a1c12max := a1c12 \cdot (1 + k3)$

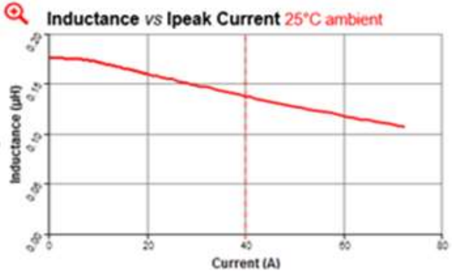
$$\boxed{\begin{array}{l} a1c12min = 3.833 \cdot 10^{-11} \\ a1c12max = 3.967 \cdot 10^{-11} \end{array}}$$

Worst Case Analysis component Tolerances

Inductor Tolerances

5. DC current at 25°C that causes an inductance drop of 30% (typ) from its value without current.

Part number[1]	Inductance[2] ±20% (µH)	DCR (mOhms)[3] typ	DCR (mOhms)[3] max	SRF typ[4] (MHz)	Isat[5] (A)	Irms (A)[6] 20°C rise	Irms (A)[6] 40°C rise
XAL7030-161ME_	0.16	1.15	1.26	158	60.0	24.9	32.5
XAL7030-301ME_	0.30	1.75	1.92	101	41.0	21.0	27.6
XAL7030-601ME_	0.60	3.00	3.30	72	36.0	18.0	23.0
XAL7030-102ME_	1.0	4.55	5.00	52	28.0	16.1	21.8
XAL7030-152ME_	1.5	7.60	8.36	39	23.5	11.9	15.0
XAL7030-222ME_	2.2	13.7	15.07	29	18.0	10.0	12.9
XAL7030-272ME_	2.7	15.7	17.30	32	12.8	9.2	11.4
XAL7030-332ME_	3.3	19.5	21.45	25	12.3	8.0	10.0
XAL7030-472ME_	4.7	26.1	30.00	21	10.1	6.9	9.0
XAL7030-562ME_	5.6	28.1	32.32	17	9.8	5.3	7.3
XAL7030-682ME_	6.8	45.0	51.75	15	8.7	4.4	6.8
XAL7030-822ME_	8.2	53.0	60.94	13	8.4	2.9	5.9
XAL7030-103ME_	10	60.4	69.46	12	7.7	2.6	5.3



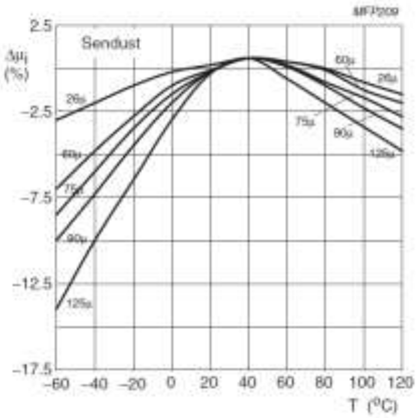
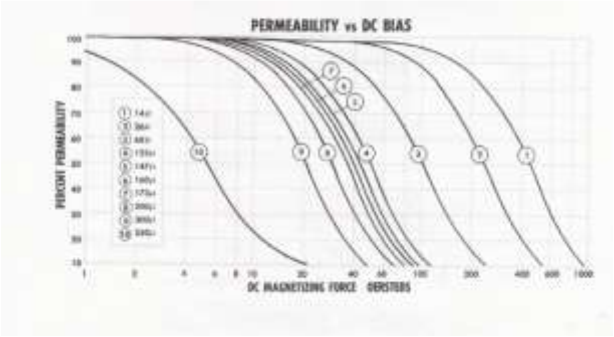


Fig.2 Initial permeability as a function of temperature.



$$L := \frac{.4 \cdot 3.14 \cdot u \cdot turns^2 \cdot (Ae)}{le \cdot 10^8}$$

Where:

Linductance = Henry's

µ = core permeability

N = number of turns

Ae = core cross-section (mm^2)

*l*e = core magnetic path length (mm)

Worst Case Analysis Inductance rolloff example

Example of saturation current

Vin =12V	Vo = .9V
Vinmax = 13.2V	Iomax = 40A
Vinmin = 10.8V	Iomin = 4A
f = 650khz	

Lout = 160nH

I_peak = 45.6A

Peak inductor current

Now what happens if I push Iomax to 60A and reduce the inductance by 30%

Vin =12V	Vo = .9V
Vinmax = 13.2V	Iomax = 60A
Vinmin = 10.8V	Iomin = 4A
f = 650khz	

Lout = 112nH

I_peak = 68.7A

Peak inductor current

Rule of thumb derate Isat by 30 to 40%

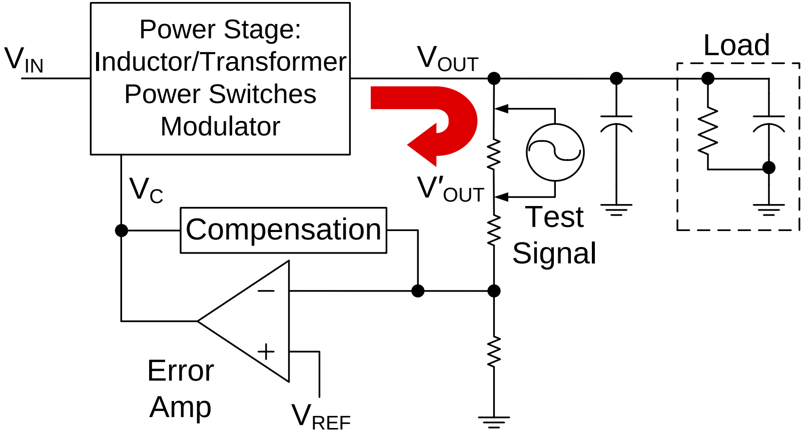
Worst Case Analysis Output regulation example

Problem statement

- What is my worst case output voltage regulation

Procedure

- Find tolerances for Vref, error-amp, and resistor divider.
- Write equation for feedback regulation
- Calculate sensitivity of variables.
- Solve equation



Worst Case Analysis Output regulation example

Reference tolerance

$tol\_TL431\_bol := 0.5 \cdot \%$ $tol\_TL431\_eol := .25 \cdot \%$ $tol\_TL431\_temp := 60 \cdot 10^{-6} \cdot delT$

- Reference Voltage Tolerance at 25°C
  - 0.5% (B Grade)
  - 1% (A Grade)
  - 2% (Standard Grade)

Reference Variation

$Vref := 2.495$

$TL431vrefmin := Vref \cdot (1 - tol\_TL431\_bol) \cdot (1 - tol\_TL431\_eol) \cdot (1 - tol\_TL431\_temp)$

$TL431vrefmin = 2.465$

$TL431vrefmax := Vref \cdot (1 + tol\_TL431\_bol) \cdot (1 + tol\_TL431\_eol) \cdot (1 + tol\_TL431\_temp)$

$TL431vrefmax = 2.525$

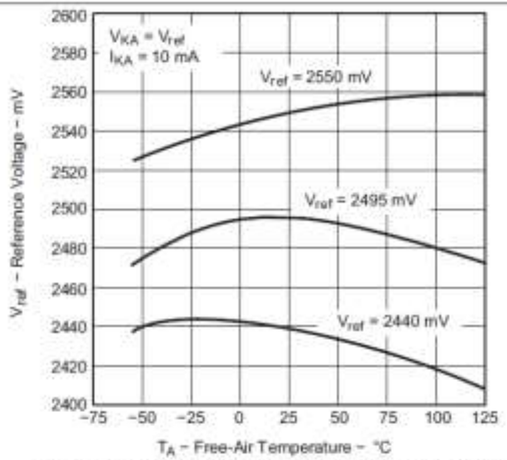
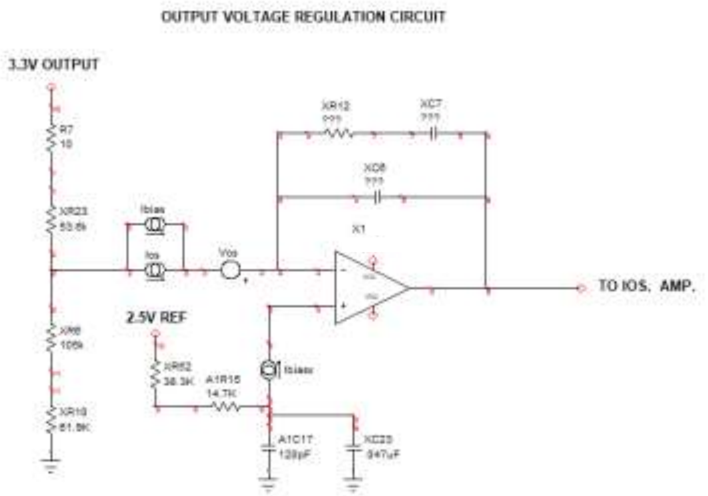


Figure 1. Reference Voltage vs Free-Air Temperature

Worst Case Analysis Output regulation example

Op-amp tolerance



Op-amp dc error sources include:

- Input offset voltage VOS
- Input bias current IB
- Input offset current IOS
- Open loop gain

From LM158 Data sheet:
Vos_bol = 7mV from -55c to 125c
Vos_temp = 15uV/c
Vos_eol = hard to find check with Manufacturer

Ib_bol = 300nA from -55c to 125c,
Ios_bol = 100nA from -55c to 125c
Ios_temp = 200pA/c, Ios_eol = hard to find check with Manufacturer

Open loop gain min = 35V/mV =35000 Open loop gain typ = 140V/mV = 140000

Worst Case Analysis Output regulation example

Below is a sensitivity calculation to show which parts should be minimized or maximized

$$\mathrm{Vonom}(\mathrm{Vref}, \mathrm{Vos}, \mathrm{Vbiasnom}, \mathrm{Vbias\_gainnom}, \mathrm{xr23}, \mathrm{r7}, \mathrm{xr10}, \mathrm{xr6}) := \begin{pmatrix} \mathrm{Vref} + \mathrm{Vos} \ldots \\ + \mathrm{Vbiasnom} \ldots \\ + \mathrm{Vbias\_gainnom} \end{pmatrix} \cdot \frac{(\mathrm{xr23} + \mathrm{r7} + \mathrm{xr10} + \mathrm{xr6})}{\mathrm{xr10} + \mathrm{xr6}}$$

$$\frac{d}{d\mathrm{Vref}} \mathrm{Vonom}(\mathrm{Vref}, \mathrm{Vos}, \mathrm{Vbiasnom}, \mathrm{Vbias\_gainnom}, \mathrm{xr23}, \mathrm{r7}, \mathrm{xr10}, \mathrm{xr6}) = 1.321$$

$$\frac{d}{d\mathrm{Vos}} \mathrm{Vonom}(\mathrm{Vref}, \mathrm{Vos}, \mathrm{Vbiasnom}, \mathrm{Vbias\_gainnom}, \mathrm{xr23}, \mathrm{r7}, \mathrm{xr10}, \mathrm{xr6}) = 1.321$$

$$\frac{d}{d\mathrm{Vbiasnom}} \mathrm{Vonom}(\mathrm{Vref}, \mathrm{Vos}, \mathrm{Vbiasnom}, \mathrm{Vbias\_gainnom}, \mathrm{xr23}, \mathrm{r7}, \mathrm{xr10}, \mathrm{xr6}) = 1.321$$

$$\frac{d}{d\mathrm{Vbias\_gainnom}} \mathrm{Vonom}(\mathrm{Vref}, \mathrm{Vos}, \mathrm{Vbiasnom}, \mathrm{Vbias\_gainnom}, \mathrm{xr23}, \mathrm{r7}, \mathrm{xr10}, \mathrm{xr6}) = 1.321$$

$$\frac{d}{d\mathrm{xr23}} \mathrm{Vonom}(\mathrm{Vref}, \mathrm{Vos}, \mathrm{Vbiasnom}, \mathrm{Vbias\_gainnom}, \mathrm{xr23}, \mathrm{r7}, \mathrm{xr10}, \mathrm{xr6}) = 1.504 \cdot 10^{-5}$$

$$\frac{d}{d\mathrm{r7}} \mathrm{Vonom}(\mathrm{Vref}, \mathrm{Vos}, \mathrm{Vbiasnom}, \mathrm{Vbias\_gainnom}, \mathrm{xr23}, \mathrm{r7}, \mathrm{xr10}, \mathrm{xr6}) = 1.504 \cdot 10^{-5}$$

$$\frac{d}{d\mathrm{xr10}} \mathrm{Vonom}(\mathrm{Vref}, \mathrm{Vos}, \mathrm{Vbiasnom}, \mathrm{Vbias\_gainnom}, \mathrm{xr23}, \mathrm{r7}, \mathrm{xr10}, \mathrm{xr6}) = -4.83 \cdot 10^{-6}$$

$$\frac{d}{d\mathrm{xr6}} \mathrm{Vonom}(\mathrm{Vref}, \mathrm{Vos}, \mathrm{Vbiasnom}, \mathrm{Vbias\_gainnom}, \mathrm{xr23}, \mathrm{r7}, \mathrm{xr10}, \mathrm{xr6}) = -4.83 \cdot 10^{-6}$$

Worst Case Analysis Output regulation example

Resistor divider tolerance

$$\text{Reqmax} := \frac{1}{\left(\frac{1}{\text{xr23max} + \text{r7max}} + \frac{1}{\text{xr10min} + \text{xr6min}}\right)}$$

$\text{Reqmax} = 4.074 \cdot 10^{4}$

$\text{a1r15max} = 1.503 \cdot 10^{4}$

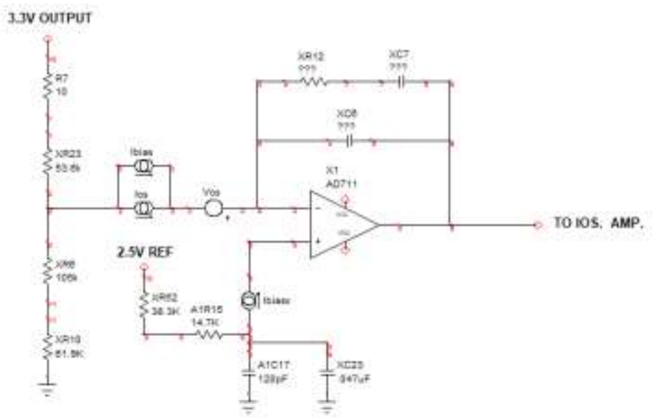
$$\text{Reqmin} := \frac{1}{\left(\frac{1}{\text{xr23min} + \text{r7min}} + \frac{1}{\text{xr10max} + \text{xr6max}}\right)}$$

$\text{Reqmin} = 4.041 \cdot 10^{4}$

$\text{a1r15min} = 1.437 \cdot 10^{4}$

Worst Case Analysis Output regulation example

OUTPUT VOLTAGE REGULATION CIRCUIT



Voltage error due to the offset current, bias current, A1r15 and Req

$$Vbiasmin := Reqmin\cdot(Ibias - Ios) - Ibias\cdot(a1r15max + xr52max) \qquad Vbiasmin = -6.685\cdot 10^{-4}$$

$$Vbiasmax := Reqmax\cdot(Ibias + Ios) - Ibias\cdot(a1r15min + xr52min) \qquad Vbiasmax = 1.748\cdot 10^{-4}$$

$$Vbiasnom := \frac{Vbiasmax + Vbiasmin}{2} \qquad Vbiasnom = -2.469\cdot 10^{-4}$$

Voltage error due to the gain in the error amplifier

Vout = (Vpos - Vneg) x Av **Vin = Vpos - Vneg** **Vbias gain = Vin**

$voh := 5$ **Voh is the Vdd voltage on the error amp. therefore the maximum ouput voltage on the error amp.**

$$Vbias\_gainmax := \frac{voh}{OLGmin} \qquad Vbias\_gainmax = 1.429\cdot 10^{-4}$$

$$Vbias\_gainmin := \frac{voh}{OLGmax} \qquad Vbias\_gainmin = 3.571\cdot 10^{-5}$$

This is the min. and max. voltage required for op-amp operation

$$Vbias\_gainnom := \frac{Vbias\_gainmax + Vbias\_gainmin}{2} \qquad Vbias\_gainnom = 8.929\cdot 10^{-5}$$

TEXAS INSTRUMENTS

Worst Case Analysis Output regulation example

The total output voltage error due to Vref, Vos, Vbias, Req, and A1r15

$$Vomax := (vrefmax + Vos + Vbiasmax + Vbias\_gainmax) \cdot \frac{(xr23max + r7max + xr10min + xr6min)}{xr10min + xr6min}$$

$$Vomax = 3.37$$

$$Vomin := (vrefmin - Vos + Vbiasmin + Vbias\_gainmin) \cdot \frac{(xr23min + r7min + xr10max + xr6max)}{xr10max + xr6max}$$

$$Vomin = 3.236$$

The percent delta for Vout is as follows

$$Vonom := 3.3$$

$$Vodelta\%pos := \frac{Vomax - Vonom}{Vonom} \cdot 100$$

$$Vodelta\%pos = 2.126$$

$$Vodelta\%neg := \frac{Vonom - Vomin}{Vonom} \cdot 100$$

$$Vodelta\%neg = 1.926$$

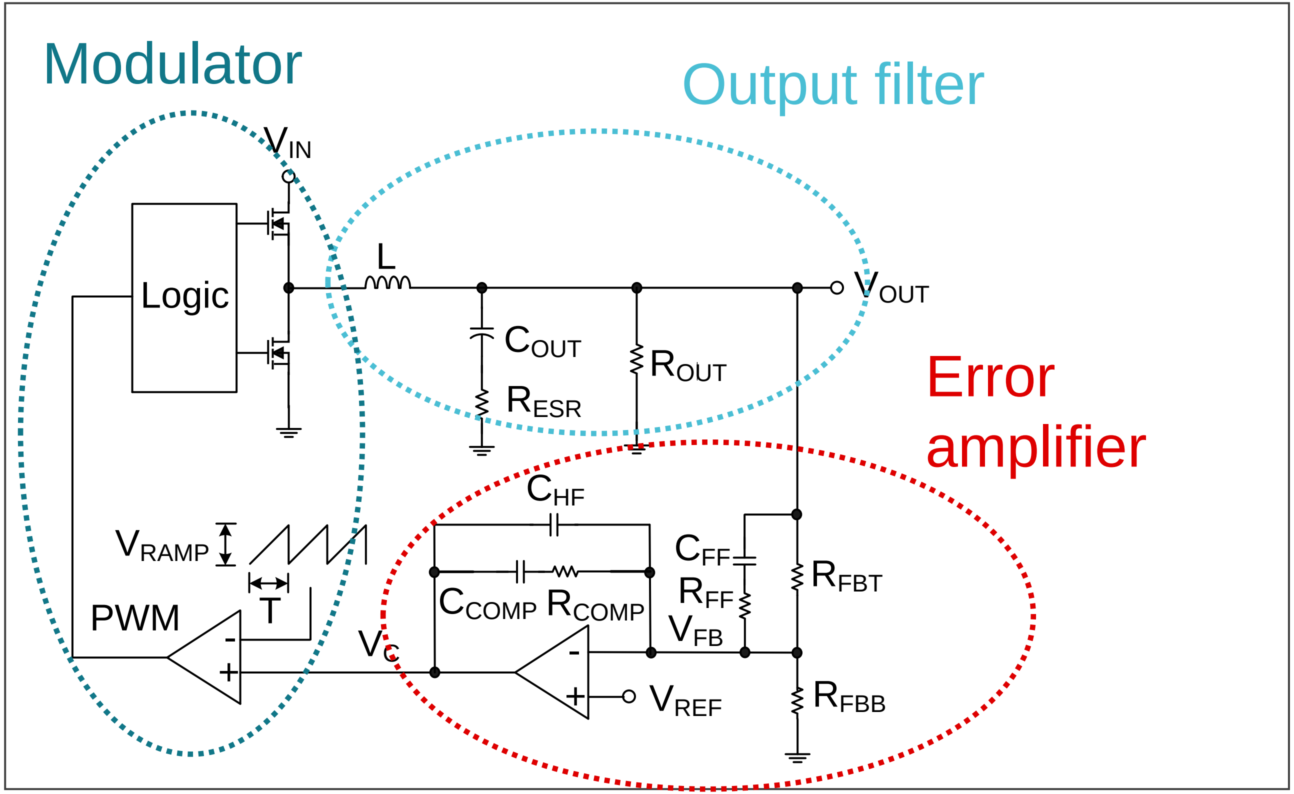
Voltage-mode buck loop stability worst case

Problem statement

- What is my worst case loop stability

Procedure

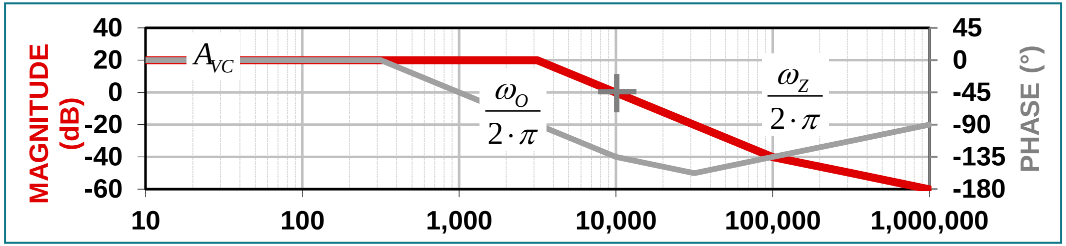
- Find tolerances for L, Cout, and compensation components.
- Write equation for the power stage, and the type 3 error amp
- Plot the bode plot for each section
- Plot the loop bode plot



Voltage-mode buck loop stability worst case

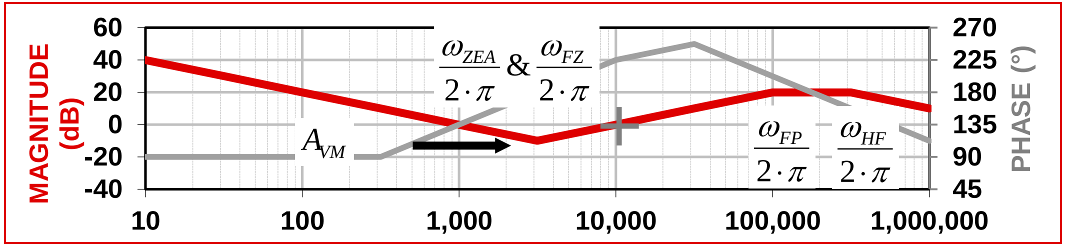
Power stage

$$\frac{\hat{v}_{OUT}}{\hat{v}_C} \approx A_{VC} \cdot \frac{1+\frac{s}{\omega_Z}}{1+\frac{s}{Q_O \cdot \omega_O}+\frac{s^2}{\omega_O^2}}$$



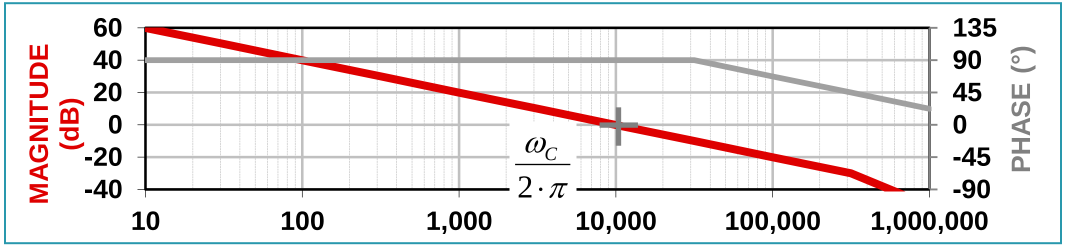
Error amplifier

$$\frac{\hat{v}_C}{\hat{v}'_{OUT}} \approx -A_{VM} \cdot \frac{\left(1+\frac{\omega_{ZEA}}{s}\right)\cdot\left(1+\frac{s}{\omega_{FZ}}\right)}{\left(1+\frac{s}{\omega_{FP}}\right)\cdot\left(1+\frac{s}{\omega_{HF}}\right)}$$

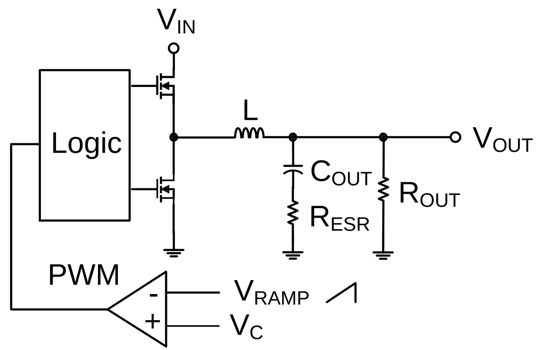


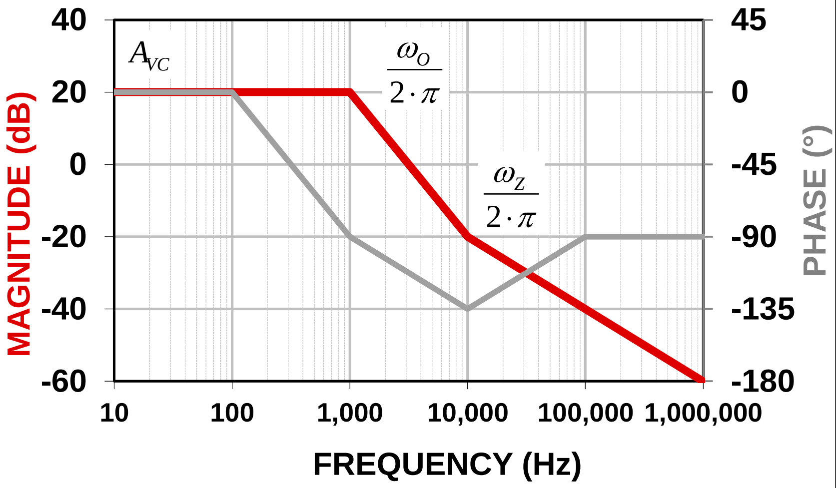
Control loop

$$\frac{\hat{v}_{OUT}}{\hat{v}'_{OUT}} = \frac{\hat{v}_{OUT}}{\hat{v}_C} \cdot \frac{\hat{v}_C}{\hat{v}'_{OUT}}$$



Voltage-mode buck power stage





$$A_{VC} = \frac{V_{IN}}{V_{RAMP}}$$

$$\omega_O = \frac{1}{\sqrt{L \cdot C_{OUT}}}$$

$$Q_O = \frac{R_{OUT}}{\sqrt{L / C_{OUT}}}$$

$$\omega_Z = \frac{1}{R_{ESR} \cdot C_{OUT}}$$

$$\frac{\hat{v}_{OUT}}{\hat{v}_C} = A_{VC} \cdot \frac{1 + \frac{s}{\omega_Z}}{1 + \frac{s}{Q_O \cdot \omega_O} + \frac{s^2}{\omega_O{}^2}}$$

Loop stability worst case

$Vinmin := 26V$

$Vinmax := 30V$

$K5 := .46$

$Vrampmin := 1.8V$

$Vrampmax := 2.2V$

$\omega := (100, 200 .. 6400000)$

$gainmin := \frac{Vinmin}{Vrampmax}$

$gainmin = 11.818$

$Cout1 := 470 \cdot 10^{-6}$

$gainmax := \frac{Vinmax}{Vrampmin}$

$gainmax = 16.667$

$RCout1 := 0.05$

$Loutmin := Lout\_act - Lout\_act \cdot 20\%$

$Loutmin = 1.76 \times 10^{-5} H$

$Loutmax := Lout\_act + Lout\_act \cdot 20\%$

$Loutmax = 2.64 \times 10^{-5} H$

$Coutmin := Cout1 \cdot (1 - K5)$

$Coutmin = 2.538 \times 10^{-4}$

$Coutmax := Cout1 \cdot (1 + K5)$

$Coutmax = 6.862 \times 10^{-4}$

$ESRCoutmax := RCout1 \cdot (1 + 20\%)$

$ESRCoutmax = 0.06$

$ESRCoutmin := RCout1 \cdot (1 - 20\%)$

$ESRCoutmin = 0.04$

$R_{Lmin} := 75 \cdot \Omega$

$R_{Lmax} := 5 \cdot \Omega$

$$fzeromax := \frac{1}{ESRCoutmin \cdot Coutmin}$$

$$fzeromin := \frac{1}{ESRCoutmax \cdot Coutmax}$$

$$fpolemax := \frac{1}{\sqrt{\frac{Loutmin}{H} \cdot Coutmin}}$$

$$fpolemin := \frac{1}{\sqrt{\frac{Loutmax}{H} \cdot Coutmax}}$$

$$Qomax := \frac{\frac{R_{Lmax}}{\Omega}}{\sqrt{\frac{\frac{Loutmin}{H}}{Coutmin}}}$$

$$Qomin := \frac{\frac{R_{Lmin}}{\Omega}}{\sqrt{\frac{\frac{Loutmax}{H}}{Coutmax}}}$$

$$PSmin(\omega) := gainmin \cdot \frac{1 + \frac{i \cdot \omega}{fzeromin}}{1 + \frac{i \cdot \omega}{Qomin \cdot fpolemin} + \frac{\omega^2}{fpolemin^2}}$$

$$PSmax(\omega) := gainmax \cdot \frac{1 + \frac{i \cdot \omega}{fzeromax}}{1 + \frac{i \cdot \omega}{Qomax \cdot fpolemax} + \frac{\omega^2}{fpolemax^2}}$$

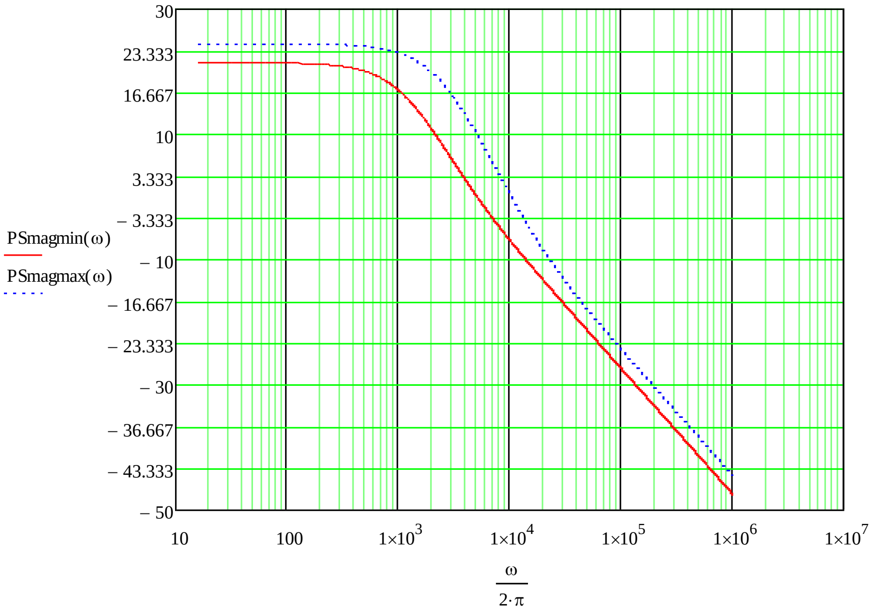
$$PSmagmin(\omega) := 20 \cdot \log(|PSmin(\omega)|)$$

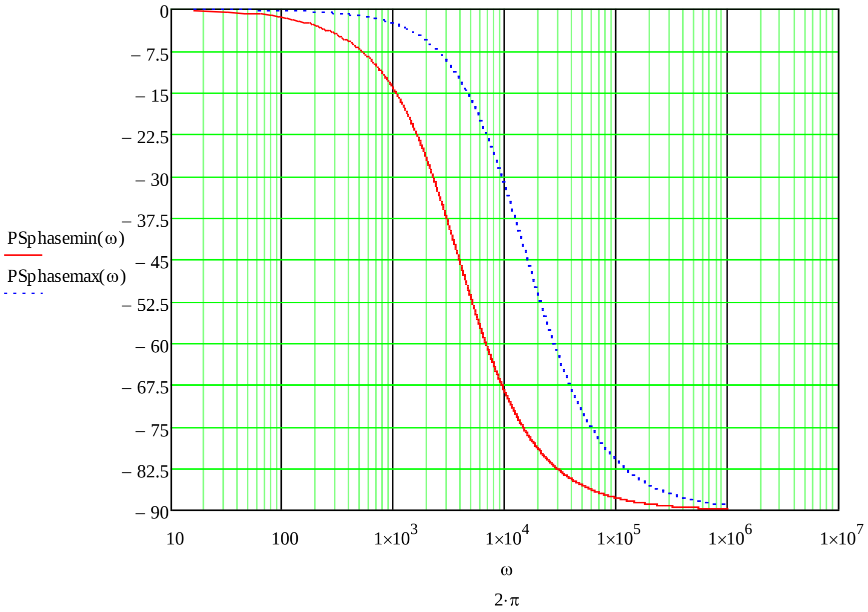
$$PSmagmax(\omega) := 20 \cdot \log(|PSmax(\omega)|)$$

$$PSphasemin(\omega) := -\frac{180}{\pi} \cdot \arg(PSmin(\omega))$$

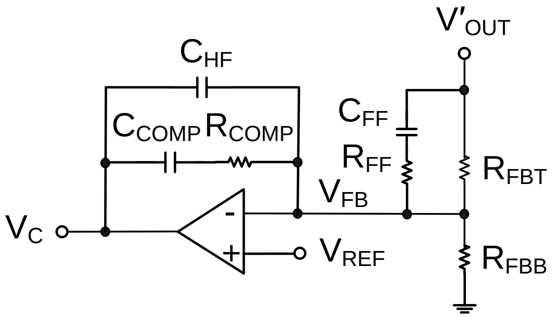
$$PSphasemax(\omega) := -\frac{180}{\pi} \cdot \arg(PSmax(\omega))$$

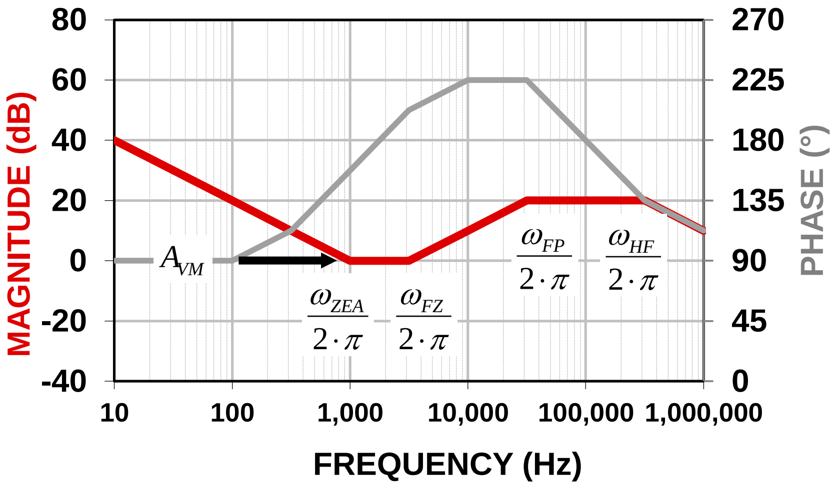
Loop stability worst case





Type III error amplifier





$$A_{VM} \approx \frac{R_{COMP}}{R_{FBT}}$$

$$\omega_{ZEA} = \frac{1}{R_{COMP} \cdot C_{COMP}} \qquad \omega_{FZ} \approx \frac{1}{R_{FBT} \cdot C_{FF}}$$

$$\omega_{FP} = \frac{1}{R_{FF} \cdot C_{FF}} \qquad \omega_{HF} \approx \frac{1}{R_{COMP} \cdot C_{HF}}$$

Assumptions: $C_{COMP} >> C_{HF}$ & $R_{FBT} >> R_{FF}$

$$\frac{\hat{v}_C}{\hat{v}'_{OUT}} = -A_{VM} \cdot \frac{\left(1+\frac{\omega_{ZEA}}{s}\right)\cdot\left(1+\frac{s}{\omega_{FZ}}\right)}{\left(1+\frac{s}{\omega_{FP}}\right)\cdot\left(1+\frac{s}{\omega_{HF}}\right)} = -\frac{A_{VM}\cdot\omega_{ZEA}}{s} \cdot \frac{\left(1+\frac{s}{\omega_{ZEA}}\right)\cdot\left(1+\frac{s}{\omega_{FZ}}\right)}{\left(1+\frac{s}{\omega_{FP}}\right)\cdot\left(1+\frac{s}{\omega_{HF}}\right)}$$

Loop stability worst case

$k1 := .007875$

$K3 := .057$

$Rfbt := 51.1K$

$Rfbb := 10K$

$Rfbtmin := Rfbt\cdot((1-k1))$

$Rfbbmin := Rfbb\cdot((1-k1))$

$Rfbtmax := Rfbt\cdot((1+k1))$

$Rfbbmax := Rfbb\cdot((1+k1))$

$Rcomp := 100K$

$Rff := 26.12K$

$Rcompmin := Rcomp\cdot((1-k1))$

$Rffmin := Rff\cdot((1-k1))$

$Rcompmax := Rcomp\cdot((1+k1))$

$Rffmax := Rff\cdot((1+k1))$

$Chf := 2200\cdot 10^{-12}$

$Chfmin := Chf\cdot(1-K3)$ $\quad Chfmin = 2.075\times 10^{-9}$

$Chfmax := Chf\cdot(1+K3)$ $\quad Chfmax = 2.325\times 10^{-9}$

$Ccomp := 1800\cdot 10^{-12}$

$Ccompmin := Ccomp\cdot(1-K3)$ $\quad Ccompmin = 1.697\times 10^{-9}$

$Ccompmax := Ccomp\cdot(1+K3)$ $\quad Ccompmax = 1.903\times 10^{-9}$

$Cff := 1800\cdot 10^{-12}$

$Cffmin := Cff\cdot(1-K3)$ $\quad Cffmin = 1.697\times 10^{-9}$

$Cffmax := Cff\cdot(1+K3)$ $\quad Cffmax = 1.903\times 10^{-9}$

$Avmmin := \frac{Rcompmin}{Rfbtmax}$ $\quad Avmmin = 1.926$

$Avmmax := \frac{Rcompmax}{Rfbtmin}$ $\quad Avmmax = 1.988$

$Wzeamin := \frac{1}{Rcompmax\cdot Ccompmax}$ $\quad Wzeamin = 5.215\times 10^{3}$

$Wzeamax := \frac{1}{Rcompmin\cdot Ccompmin}$ $\quad Wzeamax = 5.938\times 10^{3}$

$Wfzmin := \frac{1}{Rfbtmax\cdot Cffmax}$ $\quad Wfzmin = 1.021\times 10^{4}$

$Wfzmax := \frac{1}{Rfbtmin\cdot Cffmin}$ $\quad Wfzmax = 1.162\times 10^{4}$

$Wfpmin := \frac{1}{Rffmax\cdot Cffmax}$ $\quad Wfpmin = 1.997\times 10^{4}$

$Wfpmax := \frac{1}{Rffmin\cdot Cffmin}$ $\quad Wfpmax = 2.273\times 10^{4}$

$Whfmin := \frac{1}{Rcompmax\cdot Chfmax}$ $\quad Whfmin = 4.267\times 10^{3}$

$Whfmax := \frac{1}{Rcompmin\cdot Chfmin}$ $\quad Whfmax = 4.858\times 10^{3}$

$$G_{cmin}(\omega) := -\frac{Avmmin\cdot Wzeamin}{i\cdot\omega}\cdot\frac{\left[1+\frac{(i\cdot\omega)}{Wzeamin}\right]\cdot\left(1+\frac{i\cdot\omega}{Wfzmin}\right)}{\left(1+\frac{i\cdot\omega}{Wfpmax}\right)\cdot\left(1+\frac{i\cdot\omega}{Whfmax}\right)}$$

$$G_{cmax}(\omega) := -\frac{Avmmax\cdot Wzeamax}{i\cdot\omega}\cdot\frac{\left[1+\frac{(i\cdot\omega)}{Wzeamax}\right]\cdot\left(1+\frac{i\cdot\omega}{Wfzmax}\right)}{\left(1+\frac{i\cdot\omega}{Wfpmin}\right)\cdot\left(1+\frac{i\cdot\omega}{Whfmin}\right)}$$

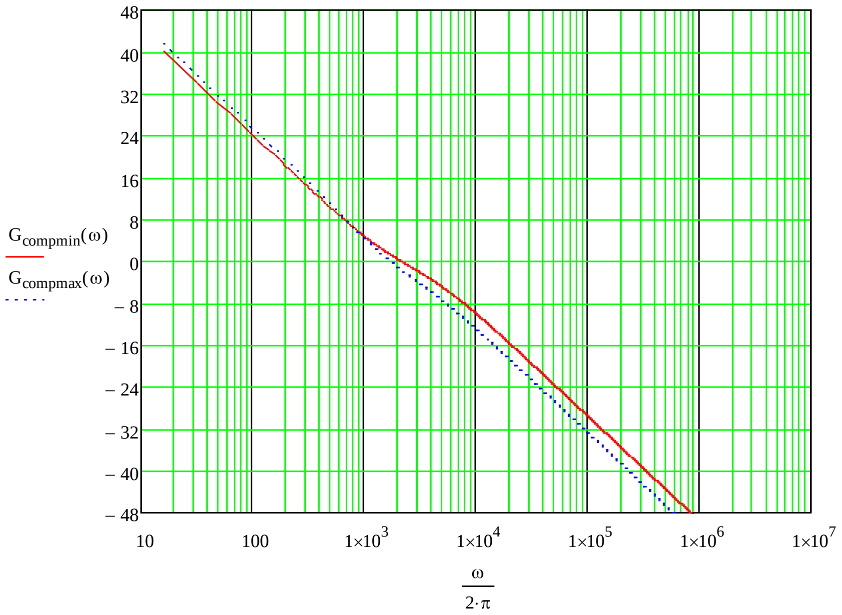
$$G_{compmin}(\omega) := 20\cdot\log\left(\left|G_{cmin}(\omega)\right|\right)$$

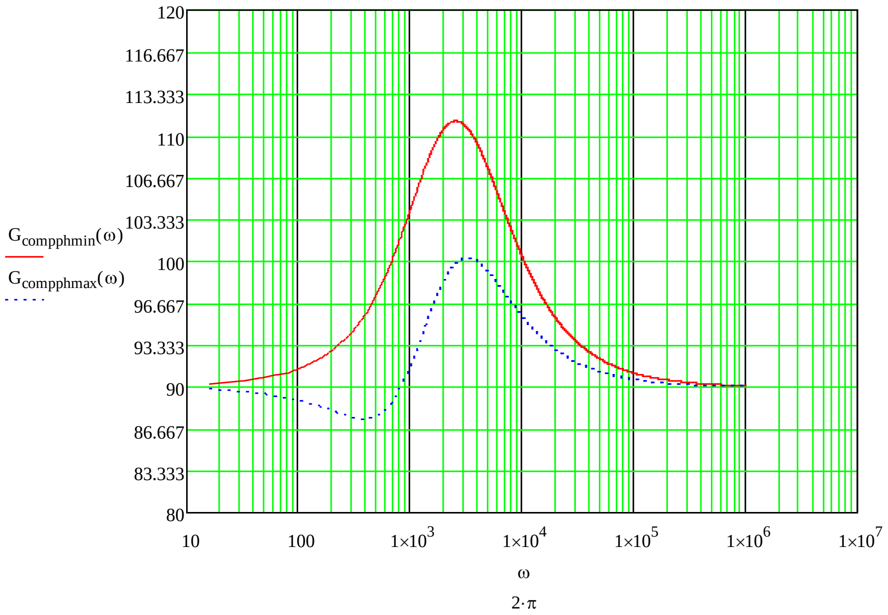
$$G_{compmax}(\omega) := 20\cdot\log\left(\left|G_{cmax}(\omega)\right|\right)$$

$$G_{compphmin}(\omega) := \frac{180}{\pi}\cdot\arg\left(G_{cmin}(\omega)\right)$$

$$G_{compphmax}(\omega) := \frac{180}{\pi}\cdot\arg\left(G_{cmax}(\omega)\right)$$

Loop stability worst case





Loop stability worst case

Open Loop Response:

$\mathrm{Gloopmin}(\omega) := -\mathrm{PSmin}(\omega)\cdot G_{cmin}(\omega)$

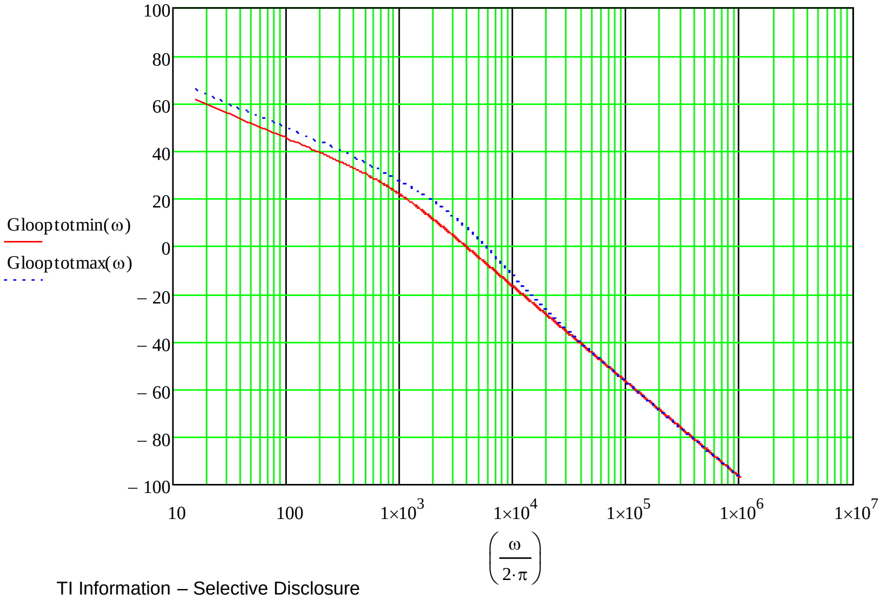
$\mathrm{Gloopmax}(\omega) := -\mathrm{PSmax}(\omega)\cdot G_{cmax}(\omega)$

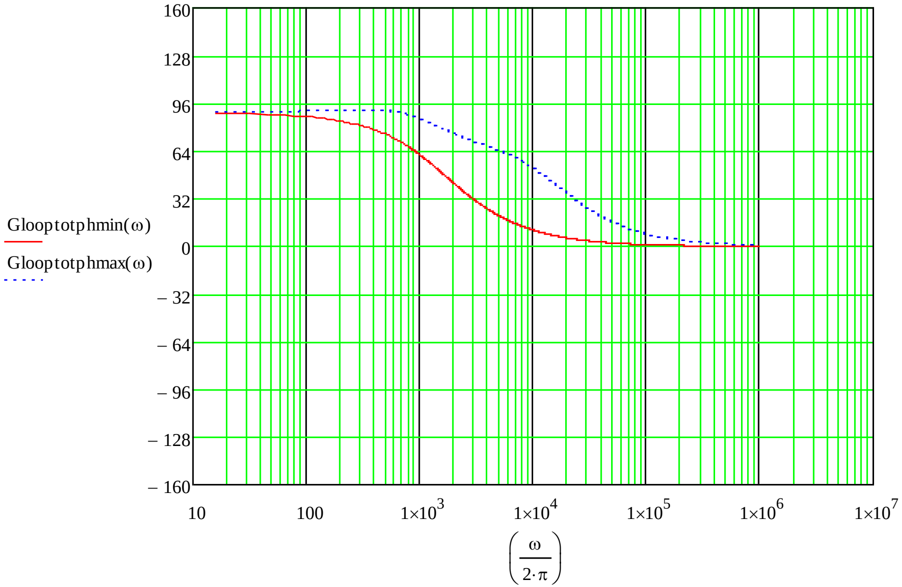
$\mathrm{Glooptotmin}(\omega) := 20\cdot\log(|\mathrm{Gloopmin}(\omega)|)$

$\mathrm{Glooptotphmin}(\omega) := -\frac{180}{\pi}\cdot\arg(\mathrm{Gloopmin}(\omega))$

$\mathrm{Glooptotmax}(\omega) := 20\cdot\log(|\mathrm{Gloopmax}(\omega)|)$

$\mathrm{Glooptotphmax}(\omega) := -\frac{180}{\pi}\cdot\arg(\mathrm{Gloopmax}(\omega))$





Worst Case Analysis MOSFET Power Dissipation Example

Problem statement

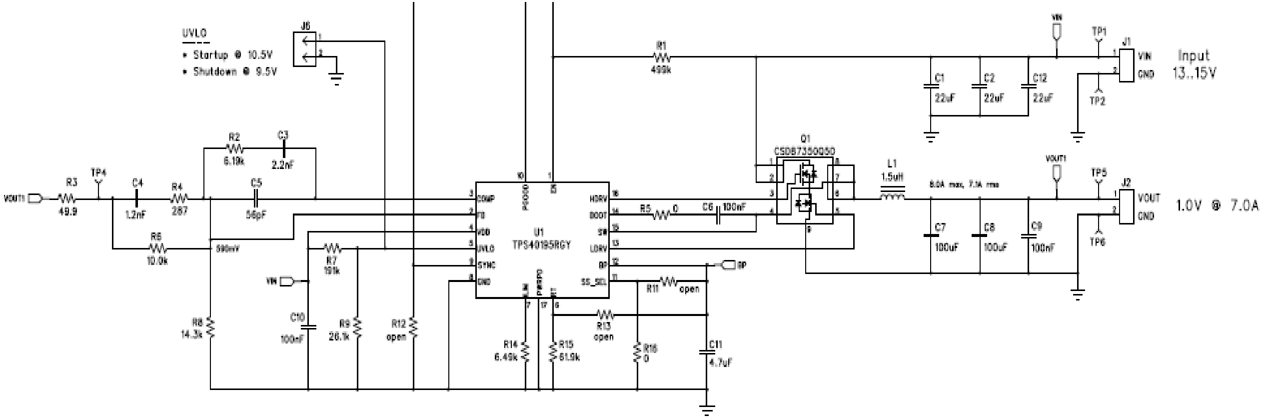
- The FET's in my PS are getting hot

Possible causes

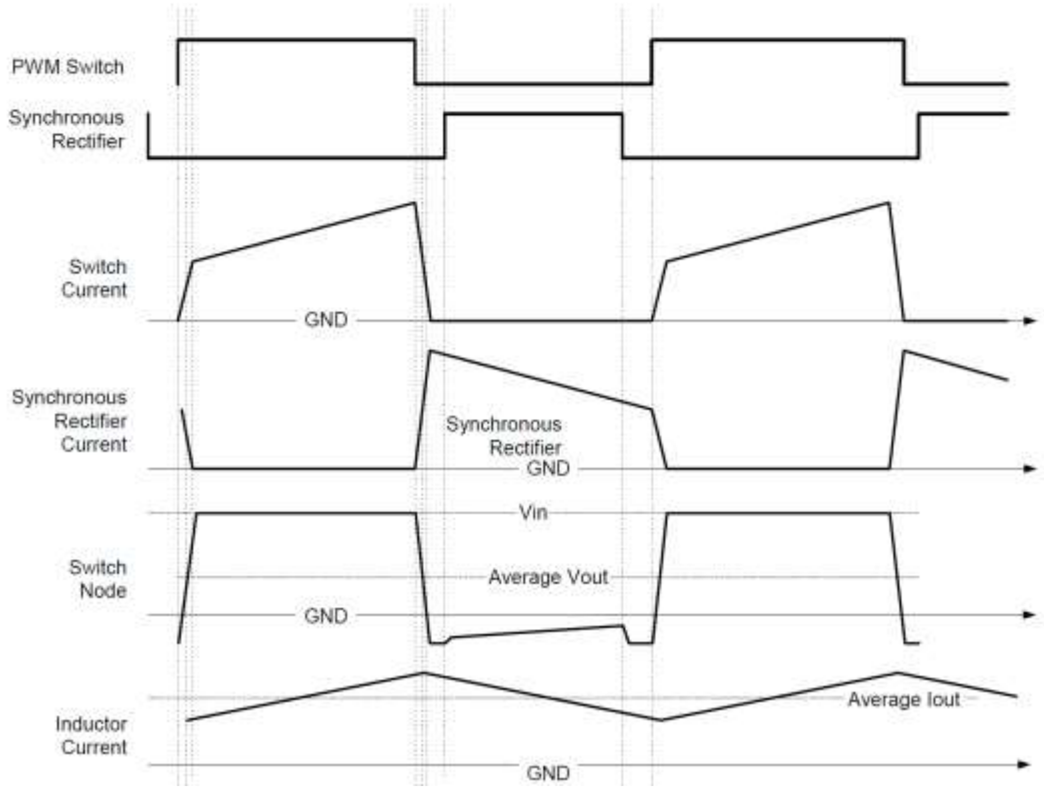
- Not enough heat sink
- Shoot through

Solution

- WCA on FET power dissipation



Worst Case Analysis MOSFET Power Dissipation Example



Procedure

- Find tolerances for Rds, Qg total gate charge, Qgs charge gate to source, Qgd charge gate to drain, Qoss output charge, body drain diode forward voltage, and controller dead time.
- Write equation and Analyze Rds conducted losses, switching loss, and gate drive loss for top FET.
- Write equation and Analyze Rds conducted losses, body drain diode loss, and gate drive loss for bottom FET
- Add up all losses

Worst Case Analysis component Tolerances

MOSFET tolerance

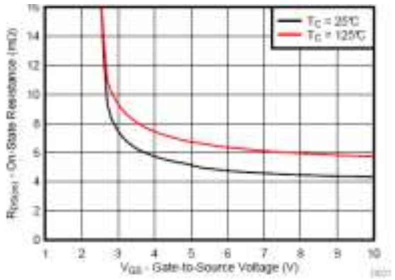


Figure 20. Control MOSFET $R_{DS(on)}$ vs V_{GS}

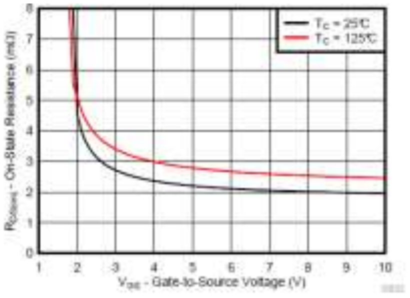


Figure 21. Sync MOSFET $R_{DS(on)}$ vs V_{GS}

CSD87350Q5D Synchronous Buck NexFET™ Power Block

Rds goes up as temp goes up

Rds_bol = 20%   Rds_tempmax = 63%   Rds_tempmin = -40%

$Rdson\_top := 5 \cdot 10^{-3} \cdot \Omega$

$Rdsmin\_top = 2.4 \times 10^{-3} \Omega$

$Rdsmax\_top = 9.78 \times 10^{-3} \Omega$

$Rdson\_bot := 1.2 \cdot 10^{-3} \cdot \Omega$

$Rdsmin\_bot = 5.76 \times 10^{-4} \Omega$

$Rdsmax\_bot = 2.347 \times 10^{-3} \Omega$

Total gate charge

$qtotal\_top := 8.4nC$ $qtotal\_bol := 30\%$ $qtotal\_bot := 20nC$

$qtotal\_min\_top = 5.88 \times 10^{-9} C$

$qtotal\_max\_top = 1.092 \times 10^{-8} C$

$qtotal\_min\_bot = 1.4 \times 10^{-8} C$

$qtotal\_max\_bot = 2.6 \times 10^{-8} C$

Gate charge gate to drain and gate to source

$Qgd\_top := 1.6nC$ $Qgd\_bol := 30\%$ $Qgs\_top := 2.6nC$ $Qgs\_bol := 30\%$

$Qgd\_min\_top = 1.12 \times 10^{-9} C$

$Qgd\_max\_top = 2.08 \times 10^{-9} C$

$Qgs\_min\_top = 1.82 \times 10^{-9} C$

$Qgs\_max\_top = 3.38 \times 10^{-9} C$

Worst Case Analysis component Tolerances

MOSFET tolerance

Qoss output charge

$Qoss\_bol := 30\%$

$Qoss\_top := 9.7nC$

$Qoss\_min\_top = 6.79 \times 10^{-9}\,C$

$Qoss\_max\_top = 1.261 \times 10^{-8}\,C$

$Qoss\_bot := 28nC$

$Qoss\_min\_bot = 1.96 \times 10^{-8}\,C$

$Qoss\_max\_bot = 3.64 \times 10^{-8}\,C$

Body drain diode forward voltage

$Vbody := .8V$

$Vbody\_bol := 25\%$

$Vbody\_temphot := 30\%$ At 125C

$Vbody\_tempcold := 22.5\%$ At -50C

$Vbody\_max = 1.3\,V$

$Vbody\_min = 0.42\,V$

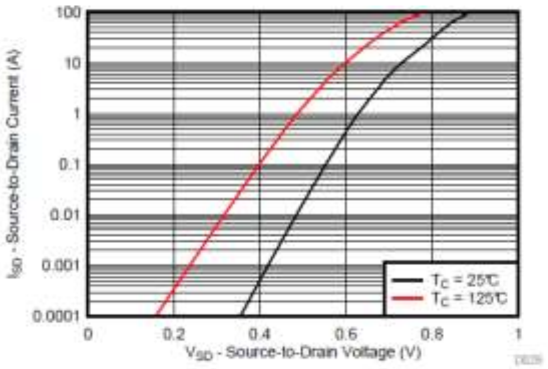


Figure 25. Sync MOSFET Body Diode

Worst Case Analysis component Tolerances

TPS40190 Controller dead time tolerance for body diode PWR calculation

$Deadtime\_HSoff\_LSon := 50ns$ $Deadtime\_LSoff\_HSon := 25ns$ $DT\_bol := 20\%$

$Deadtime\_HSoff\_LSon\_min = 4 \times 10^{-8}s$ $Deadtime\_LSoff\_HSon\_min = 2 \times 10^{-8}s$

$Deadtime\_HSoff\_LSon\_max = 6 \times 10^{-8}s$ $Deadtime\_LSoff\_HSon\_max = 3 \times 10^{-8}s$

Power block delay time tolerance for body diode PWR calculation

$Td\_FET\_bol := 30\%$ $Turnon\_dly\_HS := 7ns$ $Turnon\_dly\_LS := 8ns$ $Turnoff\_dly\_HS := 13ns$ $Turnoff\_dly\_LS := 33ns$

$Trise\_HS := 17ns$ $Trise\_LS := 10ns$ $Tfall\_HS := 2.3ns$ $Tfall\_LS := 4.7ns$

$Turnon\_dly\_HSmin = 4.9 \times 10^{-9}s$ $Trise\_HSmin = 1.19 \times 10^{-8}s$ $Turnoff\_dly\_HSmin = 9.1 \times 10^{-9}s$ $Tfall\_HSmin = 1.61 \times 10^{-9}s$

$Turnon\_dly\_HSmax = 9.1 \times 10^{-9}s$ $Trise\_HSmax = 2.21 \times 10^{-8}s$ $Turnoff\_dly\_HSmax = 1.69 \times 10^{-8}s$ $Tfall\_HSmax = 2.99 \times 10^{-9}s$

$Turnon\_dly\_LSmin = 5.6 \times 10^{-9}s$ $Trise\_LSmin = 7 \times 10^{-9}s$ $Turnoff\_dly\_LSmin = 2.31 \times 10^{-8}s$ $Tfall\_LSmin = 3.29 \times 10^{-9}s$

$Turnon\_dly\_LSmax = 1.04 \times 10^{-8}s$ $Trise\_LSmax = 1.3 \times 10^{-8}s$ $Turnoff\_dly\_LSmax = 4.29 \times 10^{-8}s$ $Tfall\_LSmax = 6.11 \times 10^{-9}s$

Worst Case Analysis MOSFET Power Dissipation Example

1) First calculate conducted loss

$Irms\_top\_fet = 10.462\,A$

$Pfet\_cond\_topmax := Irms\_top\_fet^2 \cdot Rdsmax\_top \quad Pfet\_cond\_topmax = 1.07 \cdot W$ (Cond losses)

$Pfet\_cond\_topmin := Irms\_top\_fet^2 \cdot Rdsmin\_top \quad Pfet\_cond\_topmin = 0.263 \cdot W$ (Cond losses)

$Irms\_bot\_fet = 38.677\,A$

$Pfet\_cond\_botmax := Irms\_bot\_fet^2 \cdot Rdsmax\_bot \quad Pfet\_cond\_botmax = 3.511\,W$ (Cond losses)

$Pfet\_cond\_botmin := Irms\_bot\_fet^2 \cdot Rdsmin\_bot \quad Pfet\_cond\_botmin = 0.862\,W$ (Cond losses)

2) Calculate top FET switching loss

$Ig := 1A$

$$Psw\_fet\_top := Vinmax \cdot fmax \cdot \left[\frac{Ipfet\_top \cdot (Qgd\_max\_top + Qgs\_max\_top)}{Ig} + \frac{Qoss\_max\_top + Qoss\_max\_bot}{2}\right] \quad Psw\_fet\_top = 1.502\,W$$

(Switching losses)

$Tsw := 18 \cdot ns$

$$Pd\_SW\_FET := 2 \cdot \left[\frac{1}{Tmin} \cdot \int_0^{Tsw} \left(Vinmax \cdot \frac{t}{Tsw}\right) \cdot \left[Ipfet\_top \cdot \left(1 - \frac{t}{Tsw}\right)\right] dt\right] \quad Pd\_SW\_FET = 1.517 \cdot W$$

(Switching losses)

Bottom FET has body diode voltage across it at turn on/off therefore loss is in the body diode

TEXAS INSTRUMENTS

Worst Case Analysis MOSFET Power Dissipation Example

3) Calculate gate drive losses

PARAMETER		TEST CONDITIONS	Q1 CONTROL FET			Q2 SYNC FET			UNIT
			MIN	TYP	MAX	MIN	TYP	MAX	
R_G	Series gate resistance			1.3	3		0.8	2	Ω

PARAMETER		TEST CONDITIONS	MIN	TYP	MAX	UNIT
OUTPUT DRIVERS						
R_{HDHI}	High-side driver pull-up resistance	$V_{BOOT} - V_{SW} = 4.5$ V, $I_{HDRV} = -100$ mA		3	6	Ω
R_{HDLO}	High-side driver pull-down resistance	$V_{BOOT} - V_{SW} = 4.5$ V, $I_{HDRV} = 100$ mA		1.5	3	Ω
R_{LDHI}	Low-side driver pull-up resistance	$I_{LDRV} = -100$ mA		2.5	5	Ω
R_{LDLO}	Low-side driver pull-down resistance	$I_{LDRV} = 100$ mA		0.8	1.5	Ω

$$\mathrm{Vgate} := 8\mathrm{V}$$

$$\mathrm{Pg\_dr\_top} := f \cdot \mathrm{qtotal\_max\_top} \cdot \mathrm{Vgate} \qquad \mathrm{Pg\_dr\_top} = 0.028\,\mathrm{W}$$

(Gate losses)

$$\mathrm{Act\_gate\_drive\_pwr\_top} := \frac{1.3}{3} \cdot \mathrm{Pg\_dr\_top} \qquad \mathrm{Act\_gate\_drive\_pwr\_top} = 0.012\,\mathrm{W}$$

$$\mathrm{Pg\_dr\_bot} := f \cdot \mathrm{qtotal\_max\_bot} \cdot \mathrm{Vgate} \qquad \mathrm{Pg\_dr\_bot} = 0.068\,\mathrm{W}$$

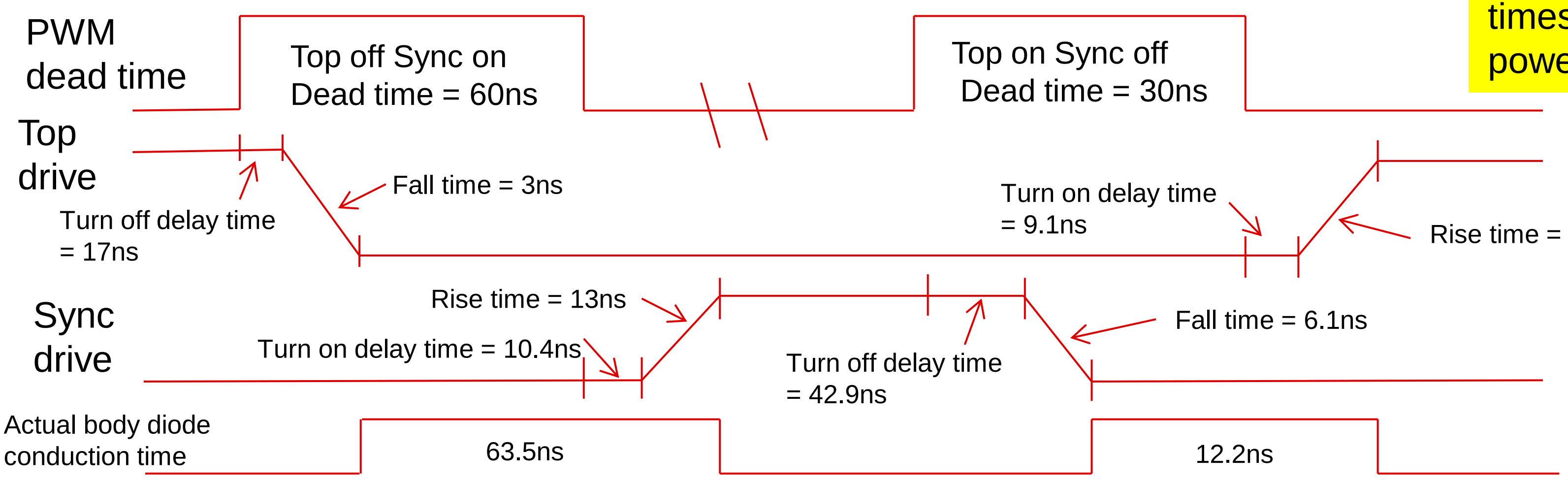
(Gate losses)

$$\mathrm{Act\_gate\_drive\_pwr\_LS} := \frac{.8}{2.5} \cdot \mathrm{Pg\_dr\_bot} \qquad \mathrm{Act\_gate\_drive\_pwr\_LS} = 0.022\,\mathrm{W}$$

Worst Case Analysis MOSFET Power Dissipation Example

3) Calculate body diode losses

Used maximum times for WC power dissipation



$$Tdelay1 := Deadtime\_HSoff\_LSon\_max - Turnoff\_dly\_HSmax - Tfall\_HSmax + Turnon\_dly\_LSmax + Trise\_LSmax \qquad Tdelay1 = 6.351 \times 10^{-8}\,s$$

$$Tdelay2 := Deadtime\_LSoff\_HSon\_max - Turnoff\_dly\_LSmax - Tfall\_LSmax + Turnon\_dly\_HSmax + Trise\_HSmax \qquad Tdelay2 = 1.219 \times 10^{-8}\,s$$

$$Pbody\_diode\_max := Vbody\_min \cdot Iomax \cdot \frac{Tdelay1 + Tdelay2}{Tmin} \qquad Pbody\_diode\_max = 0.475\,W$$

Worst Case Analysis MOSFET Power Dissipation Example

4) Add up all the top and bottom FET losses

$$Pfet\_tot\_top\_min := Pfet\_cond\_topmin + Psw\_fet\_top + Act\_gate\_drive\_pwr\_top$$

$$Pfet\_tot\_top\_min = 1.777\,W$$ (Total top FET losses Cond min)

$$Pfet\_tot\_top\_max := Pfet\_cond\_topmax + Psw\_fet\_top + Act\_gate\_drive\_pwr\_top$$

$$Pfet\_tot\_top\_max = 2.584\,W$$ (Total top FET losses max)

$$Pfet\_tot\_bot\_min := Pfet\_cond\_botmin + Act\_gate\_drive\_pwr\_LS + Pbody\_diode\_max$$

$$Pfet\_tot\_bot\_min = 1.359\,W$$ (Total bottom FET losses cond min)

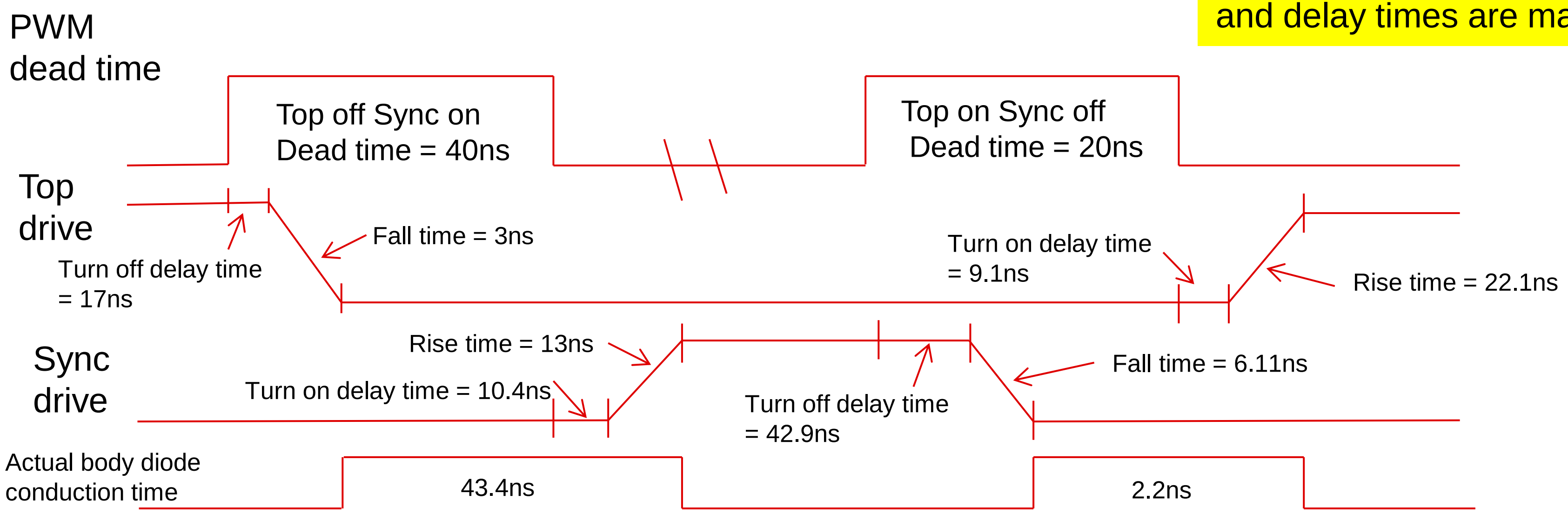
$$Pfet\_tot\_bot\_max := Pfet\_cond\_botmax + Act\_gate\_drive\_pwr\_LS + Pbody\_diode\_max$$

$$Pfet\_tot\_bot\_max = 4.008\,W$$ (Total bottom FET losses max)

Worst Case Analysis MOSFET

Cross conduction and Timing issues

Look at what happens when dead time is minimum and delay times are maximum



Summary

- Analyze the circuit to determine potential issues in the design
- Decide what type of analysis needs to be performed - EV, RSS, Monte Carlo
- Write an equation for the potential issues you found
- Determine the variables in each equation
- Determine the BOL, EOL, and temp tolerances for each variable from the manufactures DS or company APL
- Calculate the tolerances for each
- Calculate the behavioral equations using the variable tolerances to determine the worst case parameters for your design

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