PLL Design and Simulation by Dean Banerjee

ENTER THESE (yellow)...

$? := 50 \cdot deg$	Phase margin. Default is 50 degrees.
$Fc := 100 \cdot kHz$	Loop Bandwidth.
$Fcomp := 16 \cdot MHz$	Comparison Frequency
$Kvco := 40 \cdot \frac{MHz}{volt}$	VCO Tuning Constant
$K? := 30 \cdot \mu A$	Phase Detector gain do not divide by 2*π
$Fout := 1760 \cdot MHz$	RF output frequency. Choose equal to sqrt(Fmax*Fmin)
$T3T1 := 29$ %	Ratio of Poles T3/T1 expressed as a percentage. Choose from 0 to 100. 0 = second order filter. Default is 50%
$method := 1$	Set method = 0 to use a more standard set of design equations. Set method = 1 to use the Ultimate method, which is unorthodox, but does not use any approximations

CALCULATIONS USING THE ULTIMATE METHOD

$$N := \frac{Fout}{Fcomp} \qquad ?c := 2 \cdot \mathbf{p} \cdot Fc$$

SOLVE FOR T1 AND T2

$$f(x) := \frac{x}{1 + x^2} + \frac{x \cdot \frac{T3T1}{100}}{1 + \left(x \cdot \frac{T3T1}{100}\right)^2} \qquad g(x) := \frac{1 + \sqrt{1 - 4 \cdot f(x)^2}}{2 \cdot f(x)}$$

This finds wcT2 as a function of wcT1 (or x)

$$x := 3 \cdot 10^{-5}$$

$$T1 := \frac{\mathrm{root}\left[g(x) - x \cdot g(x) \cdot x \cdot \frac{T3T1}{100} - x - x \cdot \frac{T3T1}{100} - \tan(?)\left[1 - x \cdot x \cdot \frac{T3T1}{100} + g(x) \cdot \left(x + x \cdot \frac{T3T1}{100}\right)\right], x\right]}{?c}$$

$$T2 := \frac{g(?c \cdot T1)}{?c} \qquad T3 := \frac{T3T1}{100} \cdot T1$$

$$T1 = 4.277 \times 10^{-7}\, s$$

$$T2 = 4.256 \times 10^{-6}\, s$$

$$T3 = 1.24 \times 10^{-7}\, s$$

SET UP SYSTEM OF 4 EQUATIONS AND 4 UNKNOWNS

$$k1 := \left(\frac{K? \cdot Kvco}{N}\right) \cdot \sqrt{\frac{1 + (?c \cdot T2)^2}{\left[1 + (?c \cdot T1)^2\right] \cdot \left[1 + (?c \cdot T3)^2\right]}} \cdot \frac{1}{?c^2}$$

$k1 = 0.076 \cdot nF$

$$k2 := (T1 + T3) \cdot k1$$

$k2 = 4.191 \times 10^{-8} \cdot sec \cdot nF$

$$k3 := \frac{T3 \cdot T1 \cdot k1}{T2}$$

$k3 = 9.467 \times 10^{-10} \cdot sec \cdot nF$

USE THESE EQUATIONS TO FIND THE MAXIMUM VALUE FOR k4

$$A := k3^2$$

$A = 0 \cdot sec^2 \cdot nF^2$

$$B := 2 \cdot k2 \cdot k3 - 4 \cdot T2 \cdot k1 \cdot k3$$

$B = -1.145 \times 10^{-15} \cdot sec^2 \cdot n$

$$C := k2^2 - 4 \cdot T2 \cdot k3 \cdot k1$$

$C = 0 \cdot sec^2 \cdot nF^2$

$$k4min := \frac{-B - \sqrt{B^2 - 4 \cdot A \cdot C}}{2 \cdot A}$$

$k4min = 0.465$

$$k4max := \frac{-B + \sqrt{B^2 - 4 \cdot A \cdot C}}{2 \cdot A}$$

$k4max = 1.277 \times 1$ $k4 := k4min$

NOW SOLVE FOR C1 AND THE OTHER COMPONENTS

$$A := T2 \cdot (k4 + 1)$$
$$B := -k2 - k3 \cdot k4$$
$$C := k3 \cdot k1$$

$A = 6.234 \times 10^{-6} s$

$B = -4.235 \times 10^{-5} \cdot sec \cdot pF$

$C = 7.191 \times 10^{-5} \cdot sec \cdot pF^2$

SOLVE FOR COMPONENTS

$$C1 := \frac{-B}{2 \cdot A} \qquad C3 := k4 \cdot C1$$

$$C2 := k1 - C3 - C1 \qquad R3 := \frac{k3}{C1 \cdot C3}$$

$$R2 := \frac{T2}{C2}$$

CALCULATIONS USING THE STANDARD METHOD

$$T1 := \frac{\left(\frac{1}{\cos(?)}\right) - \tan(?)}{?c \cdot \left(\frac{T3T1}{100} + 1\right)} \qquad T3 := \frac{T3T1}{100} \cdot T1 \qquad T2 := \frac{1}{\left[?c^2 \cdot (T1 + T3)\right]}$$

$$C1s := \frac{T1}{T2} \cdot \frac{K? \cdot Kvco}{?c^2 \cdot N} \cdot \left[\frac{1 + ?c^2 \cdot T2^2}{\left(1 + ?c^2 \cdot T1^2\right) \cdot \left(1 + ?c^2 \cdot T3^2\right)}\right]^{\frac{1}{2}} \qquad C2s := C1s \cdot \left(\frac{T2}{T1} - 1\right) \qquad C3s := \frac{C1s}{10}$$

$$R2s := \frac{T2}{C2s} \qquad R3s := \frac{T3}{C3s}$$

ASSIGN COMPONENT VALUES BASED ON USER'S SELECTION OF EITHER THE STANDARD OR ULTIMATE METHOD

C1 := if(method > 0.5, C1, C1s) C3 := if(method > 0.5, C3, C3s) R3 := if(method > 0.5, R3, R3s)

C2 := if(method > 0.5, C2, C2s) R2 := if(method > 0.5, R2, R2s)

THE CALCULATED VALUES ARE SHOWN BELOW

C1 = 3.3961495·pF C2 = 70.985·pF C3 = 1.5787201·pF

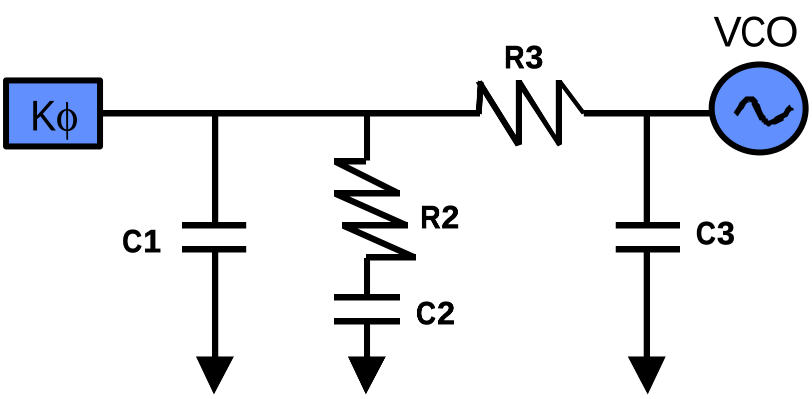
R2 = 59.9571793·kO R3 = 176.5631296·kO

ENTER PARAMETERS HERE

K? := K? Fcomp := Fcomp Fout := Fout Kvco := Kvco

C1 := C1 R3 := R3 C2 := C2 C3 := C3 R2 := R2

Changes to actual loop filter: C3 := 3pF



CALCULATE PARAMETERS

$$N := \frac{Fout}{Fcomp} \qquad ? := \frac{R2 \cdot C2}{2} \cdot \sqrt{\frac{K? \cdot Kvco}{N \cdot (C1 + C2 + C3)}} \qquad ?n := \sqrt{\frac{K? \cdot Kvco}{N \cdot (C1 + C2 + C3)}}$$

$N = 110$ $\qquad ? = 0.799$ $\qquad \frac{?n}{2 \cdot \mathbf{p}} = 59.758 \cdot kHz$

CALCULATE THE TRUE POLES AND ZERO

$$T2 := R2 \cdot C2 \qquad x := \frac{C2 \cdot C3 \cdot R2 + C1 \cdot C2 \cdot R2 + C1 \cdot C3 \cdot R3 + C2 \cdot C3 \cdot R3}{C1 + C2 + C3}$$

This is T1+T3

$$y := \frac{R2 \cdot R3 \cdot C1 \cdot C2 \cdot C3}{C1 + C2 + C3}$$

This is T1*T3

$$T1 := \frac{x + \sqrt{x^2 - 4 \cdot y}}{2} \qquad T3 := \frac{x - \sqrt{x^2 - 4 \cdot y}}{2} \qquad junk := T3$$

Make sure that T1 and T3 are not switched

$T3 := if(T3 > T1, T1, T3)$ $\qquad T1 := if(T3 > T1, junk, T1)$

Time Constant	Filter Pole	Filter Zero
$T1 = 7.244 \times 10^{-7} s$	$\frac{1}{T1} = 1.381 \times 10^3 \cdot kHz$	n/a
$T2 = 4.256 \times 10^{-6} s$	n/a	$\frac{1}{T2} = 234.96 \cdot kHz$
$T3 = 1.366 \times 10^{-7} s$		
$\frac{T3}{T1} = 18.857 \cdot \%$	$\frac{1}{T3} = 7.321 \times 10^3 \cdot kHz$	n/a

DEFINE LOOP PARAMETERS

$$Z(?) := \frac{1 + T2 \cdot i \cdot ?}{i \cdot ? \cdot (C1 + C2 + C3) \cdot (1 + i \cdot ? \cdot T1) \cdot (1 + i \cdot ? \cdot T3)}$$

Loop Filter Impedance

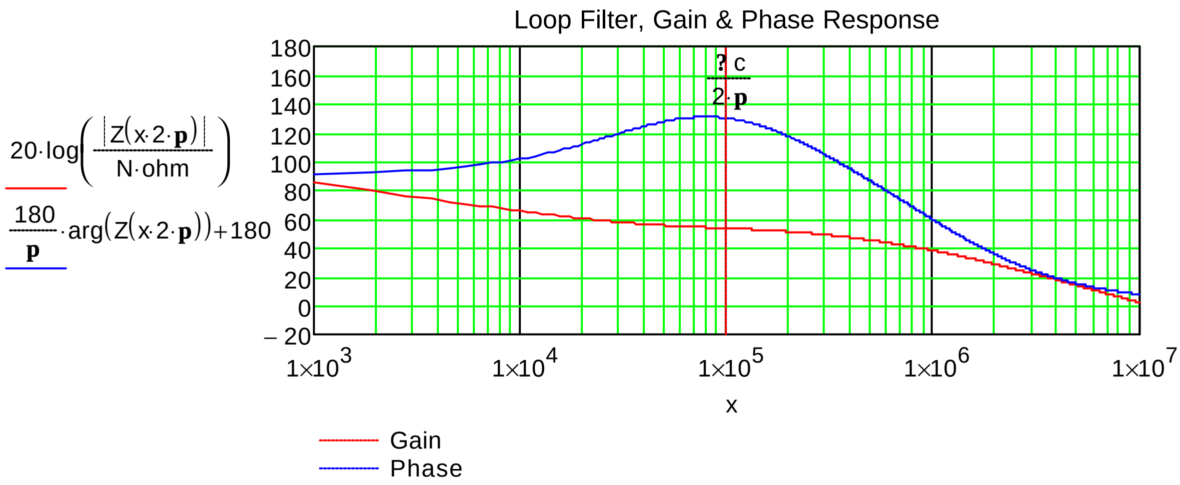
$$G(?) := \frac{K? \cdot Kvco \cdot Z(?)}{i \cdot ?}$$

Forward Loop Gain

$$CL(?) := \frac{G(?)}{1 + \frac{G(?)}{N}}$$

Closed Loop Gain

$$x := 100 \cdot Hz, 1000 \cdot Hz .. \frac{100 \cdot ?c}{2 \cdot \mathbf{p}}$$



BANDWIDTH AND PHASE MARGIN

$? := 600.0 \cdot kHz$ Initial Guess for Loop Bandwidth

$?c := root(|G(?)| - N, ?)$ $\frac{?c}{2 \cdot p} = 94.142 \cdot kHz$ Loop Bandwidth

$? := ?c$ $\frac{root(|CL(?)| - N, ?)}{2 \cdot p} = 135.097 \cdot kHz$ 0 db Bandwidth

$\frac{root\left(|CL(?)| - \frac{N}{\sqrt{2}}, ?\right)}{2 \cdot p} = 166.638 \cdot kHz$ 3 db Bandwidth

$arg(G(?c)) \cdot \frac{180}{p} + 180 = 40.523$ Phase Margin

ADDED SPURIOUS ATTENUATION (THIRD ORDER FILTERS ONLY)

$$spur(?) := 10 \cdot log\left[\frac{1 + [?c \cdot (T1 + T3)]^2}{1 + [? \cdot (T1 + T3)]^2} \cdot \frac{1 + (? \cdot T1)^2}{1 + (?c \cdot T1)^2} \cdot \frac{1 + (? \cdot T3)^2}{1 + (?c \cdot T3)^2}\right]$$

$spur(2 \cdot p \cdot Fcomp) = 21.518$ Additional Reference freq (Fc) Atteuenation

$spur\left(\frac{1}{4} \cdot 2 \cdot p \cdot Fcomp\right) = 9.812$ Attenuation at Fc/4

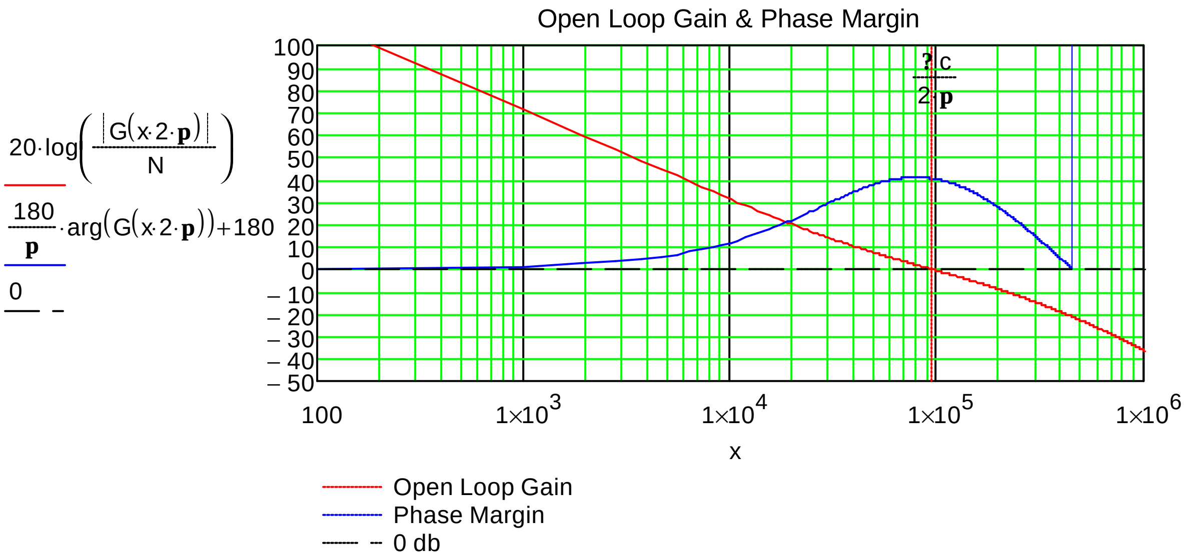
OPTIMIZATION INDEX (100% = Most Optimized)

$$Index := \frac{\frac{T2}{1+(?c \cdot T2)^2}}{\frac{T1}{1 + (?c \cdot T1)^2} + \frac{T3}{1 + (?c \cdot T3)^2}}$$

$Index := if\left(Index > 1, \frac{1}{Index}, Index\right)$

$Index = 77.572 \cdot \%$ This is the Optimization Index in Percent

DISPLAY BODE PLOT



PHASE NOISE PROFILE FOR A NOISELESS VCO

$Noise1Hz := -202$ dbc/Hz — 1 Hz Normalized Phase Detector Phase Noise, max typically -207

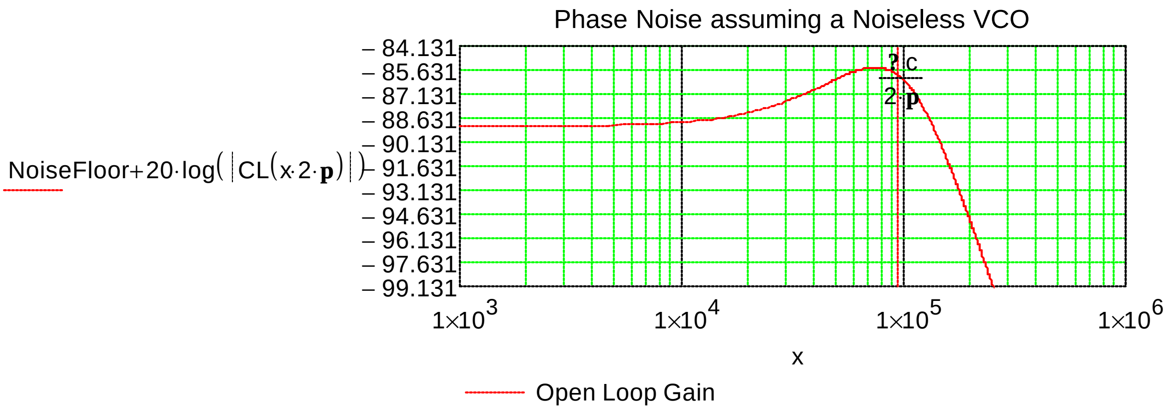
$$NoiseFloor := Noise1Hz + 10 \cdot \log\left(\frac{Fcomp}{Hz}\right)$$

$NoiseFloor = -129.959$ dbc/Hz — Noise Floor of PLL (in loop)

$NoiseFloor + 20 \cdot \log(N) = -89.131$ dbc/Hz — In loop Phase Noise

$$\sqrt{\frac{2 \cdot sec}{\pi} \cdot \int_{10 \cdot Hz}^{4 \cdot \omega c} 10^{\frac{NoiseFloor}{10}} \cdot (|CL(\omega)|)^2 \, d\omega} = 2.114 \cdot deg$$

RMS Phase Error



TRANSIENT ANALYSIS

$f2 := 1760 \cdot MHz$ Final Frequency

$f1 := 1860 \cdot MHz$ Starting Frequency

$R3 := \max\left(\begin{pmatrix} R3 \\ 1 \cdot \Omega \end{pmatrix}\right)$ $C3 := \max\left(\begin{pmatrix} C3 \\ 1 \cdot pF \end{pmatrix}\right)$

$N := \frac{f2}{Fcomp}$ $den2 := C1 + C2 + C3$ $den3 := C2 \cdot C3 \cdot R2 + C1 \cdot C2 \cdot R2 + C1 \cdot C3 \cdot R3 + C2 \cdot C3 \cdot R3$

$den4 := R2 \cdot R3 \cdot C1 \cdot C2 \cdot C3$

$den1 := \frac{K? \cdot Kvco \cdot C2 \cdot R2}{N}$ $num0 := \frac{K? \cdot Kvco \cdot (f2 - f1)}{N}$

$den0 := \frac{K? \cdot Kvco}{N}$ $num1 := num0 \cdot R2 \cdot C2$

$$v := \begin{pmatrix} \frac{den0}{den4} \cdot sec^4 \\ \frac{den1}{den4} \cdot sec^3 \\ \frac{den2}{den4} \cdot sec^2 \\ \frac{den3}{den4} \cdot sec \\ 1 \end{pmatrix} \qquad v = \begin{pmatrix} 1.425 \times 10^{24} \\ 6.064 \times 10^{18} \\ 1.011 \times 10^{13} \\ 8.702 \times 10^{6} \\ 1 \end{pmatrix}$$

$p := polyroots(v) \cdot sec^{-1}$

$$p = \begin{pmatrix} -7.451 \times 10^{6} \\ -4.451 \times 10^{5} \\ -4.028 \times 10^{5} - 5.171i \times 10^{5} \\ -4.028 \times 10^{5} + 5.171i \times 10^{5} \end{pmatrix} s^{-1}$$

These are the poles

$$A_0 := \frac{\frac{num0}{den4}}{(p_0 - p_1) \cdot (p_0 - p_2) \cdot (p_0 - p_3)} \qquad A_0 = 4.072 \times 10^{11} \, s^{-2}$$

$$A_1 := \frac{\frac{num0}{den4}}{(p_1 - p_0) \cdot (p_1 - p_2) \cdot (p_1 - p_3)} \qquad A_1 = -7.555 \times 10^{13} \, s^{-2}$$

$$A_2 := \frac{\frac{num0}{den4}}{(p_2 - p_0) \cdot (p_2 - p_1) \cdot (p_2 - p_3)} \qquad A_2 = \left(3.757 \times 10^{13} - 3.103i \times 10^{11}\right) s^{-2}$$

$$A_3 := \frac{\frac{num0}{den4}}{(p_3 - p_0) \cdot (p_3 - p_1) \cdot (p_3 - p_2)} \qquad A_3 = \left(3.757 \times 10^{13} + 3.103i \times 10^{11}\right) s^{-2}$$

4 Pole Analysis

$k := 0..\ 4000$ $i := 0..\ 3$

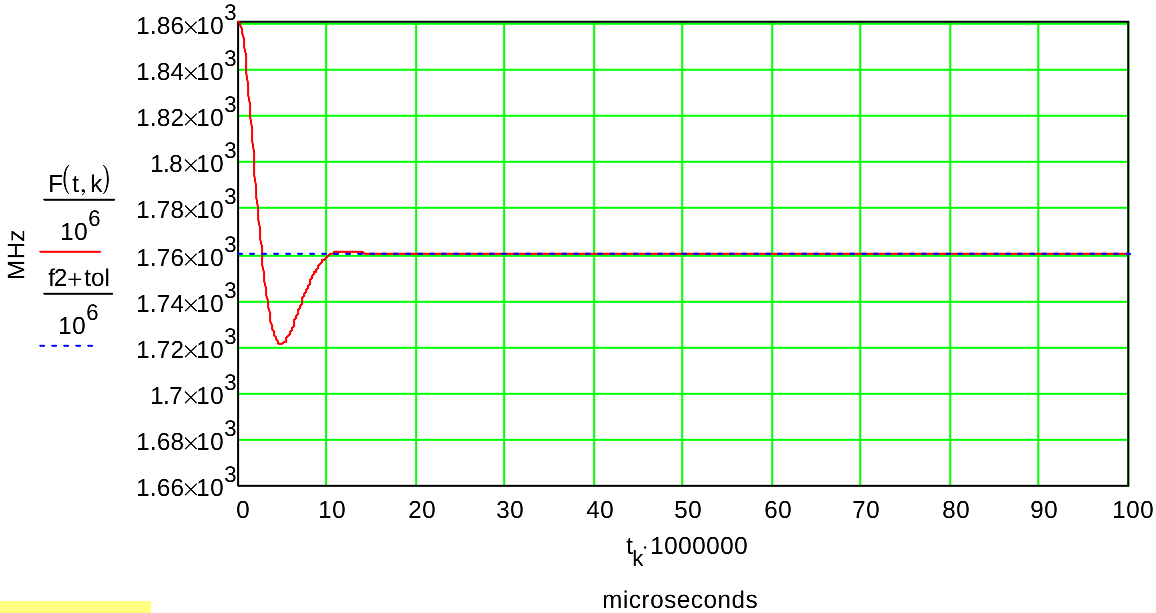
$$t_k := \frac{k}{10000000} \cdot sec \qquad F(t,k) := f2 + \sum_i \left[A_i \cdot e^{(p_i \cdot t_k)} \cdot \left(\frac{1}{p_i} + R2 \cdot C2 \right) \right]$$

$range := 100 \cdot 10^{(-6)} \cdot sec$ — Maximum Range of the X axis

$tol := -0.01 \cdot MHz$ — Tolerance Marker for Lock Time Measurments

$span := 200 \cdot MHz$ — Vertical Span of the Plot

$center := 1760 \cdot MHz$ — Center Frequency



$span := 0.2 \cdot MHz$