# PLL Design and Simulation by Dean Banerjee

## ENTER THESE (yellow)...

| | |
|---|---|
| $\phi := 50 \cdot deg$ | 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 |
| $K\phi := 30 \cdot \mu A$ | 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.<br>Set method = 1 to use the Ultimate method, which is unorthodox, but does not use any approximations |

## CALCULATIONS USING THE ULTIMATE METHOD

$$N := \frac{Fout}{Fcomp} \qquad \omega c := 2 \cdot \pi \cdot Fc$$

### 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 )

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

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

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

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

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

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

## SET UP SYSTEM OF 4 EQUATIONS AND 4 UNKNOWNS

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

$k1 = 0.076\,nF$

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

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

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

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

## USE THESE EQUATIONS TO FIND THE MAXIMUM VALUE FOR k4

$$A := k3^2$$

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

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

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

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

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

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

$k4min = 0.465$

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

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

## NOW SOLVE FOR C1 AND THE OTHER COMPONENTS

$$A := T2 \cdot (k4 + 1)$$

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

$$B := -k2 - k3 \cdot k4$$

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

$$C := k3 \cdot k1$$

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

## 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

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

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

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

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

$C1 := \text{if}(\text{method} > 0.5, C1, C1s)$ $C3 := \text{if}(\text{method} > 0.5, C3, C3s)$ $R3 := \text{if}(\text{method} > 0.5, R3, R3s)$

$C2 := \text{if}(\text{method} > 0.5, C2, C2s)$ $R2 := \text{if}(\text{method} > 0.5, R2, R2s)$

## THE CALCULATED VALUES ARE SHOWN BELOW

$C1 = 3.3961487\,pF$ $C2 = 70.985\,pF$ $C3 = 1.5787196\,pF$

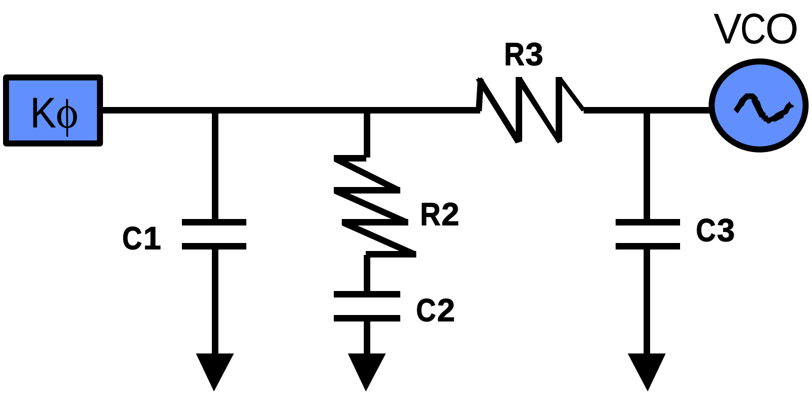
$R2 = 59.9571783\,k\Omega$ $R3 = 176.5631365\,k\Omega$

## ENTER PARAMETERS HERE

$K\phi := K\phi$ $Fcomp := Fcomp$ $Fout := Fout$ $Kvco := Kvco$

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

Changes to actual loop filter: $C3 := 3pF$



## CALCULATE PARAMETERS

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

$N = 110$    $\zeta = 0.799$    $\frac{\omega n}{2 \cdot \pi} = 59.758\,kHz$

## CALCULATE THE TRUE POLES AND ZERO

$T2 := R2 \cdot C2$    $x := \frac{C2 \cdot C3 \cdot R2 + C1 \cdot C2 \cdot R2 + C1 \cdot C3 \cdot R3 + C2 \cdot C3 \cdot R3}{C1 + C2 + C3}$    This is T1+T3

$y := \frac{R2 \cdot R3 \cdot C1 \cdot C2 \cdot C3}{C1 + C2 + C3}$    This is T1*T3

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

Make sure that T1 and T3 are not switched

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

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

## DEFINE LOOP PARAMETERS

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

$G(\omega) := \frac{K\phi \cdot Kvco \cdot Z(\omega)}{i \cdot \omega}$    Forward Loop Gain

$CL(\omega) := \frac{G(\omega)}{1 + \frac{G(\omega)}{N}}$    Closed Loop Gain

## BANDWIDTH AND PHASE MARGIN

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

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

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

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

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

## ADDED SPURIOUS ATTENUATION ( THIRD ORDER FILTERS ONLY )

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

$spur(2 \cdot \pi \cdot Fcomp) = 21.518$ Additional Reference freq (Fc) Atteunation

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

## OPTIMIZATION INDEX ( 100% = Most Optimized )

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

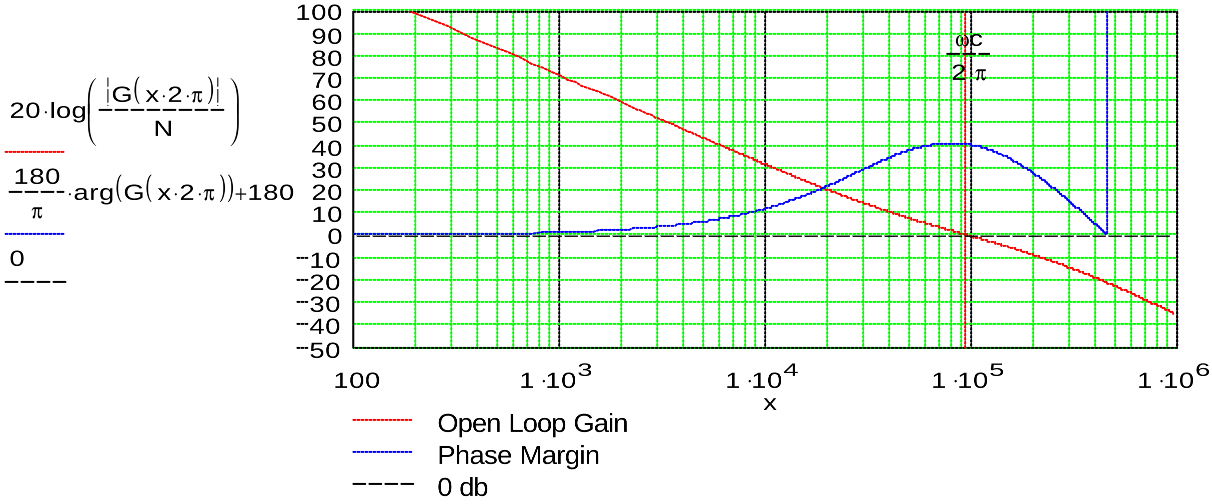
$$Index := if\left(Index > 1, \frac{1}{Index}, Index\right)$$

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

## DISPLAY BODE PLOT

$x := 10 \cdot Hz, 100 \cdot Hz .. \frac{10 \cdot \omega c}{2 \cdot \pi}$

Open Loop Gain and Phase Margin




## PHASE NOISE PROFILE FOR A NOISELESS VCO

$Noise1Hz := -206$ dbc/Hz

1 Hz Normalized Phase Detector Phase Noise, max typically -207

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

$NoiseFloor = -133.959$ dbc/Hz

Noise Floor of PLL

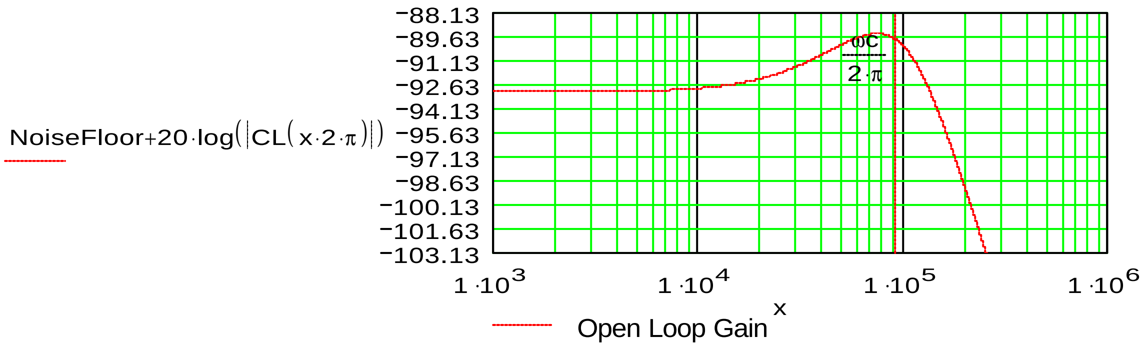
$NoiseFloor + 20 \cdot \log(N) = -93.131$ dbc/Hz

In loop Phase Noise

$$\sqrt{\frac{2 \cdot sec}{\pi} \cdot \int_{10 \cdot Hz}^{4 \cdot \omega c} 10^{\frac{NoiseFloor}{10}} \cdot \left(\left|CL(\omega)\right|\right)^2 \, d\omega} = 1.334 \, deg$$

RMS Phase Error

Phase Noise Profile for Noiseless VCO



## TRANSIENT ANALYSIS

$f2 := 1760 \cdot MHz$ Final Frequency

$f1 := 1860 \cdot MHz$ Starting Frequency

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

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

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

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

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

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

$$p := \text{polyroots}(v) \cdot sec^{-1} \qquad p = \begin{pmatrix} -7.451 \times 10^{6} \\ -4.451 \times 10^{5} \\ -4.028 \times 10^{5} - 5.171i \times 10^{5} \\ -4.028 \times 10^{5} + 5.171i \times 10^{5} \end{pmatrix} sec^{-1}$$

These are the poles

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

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

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

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

## 4 Pole Analysis

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

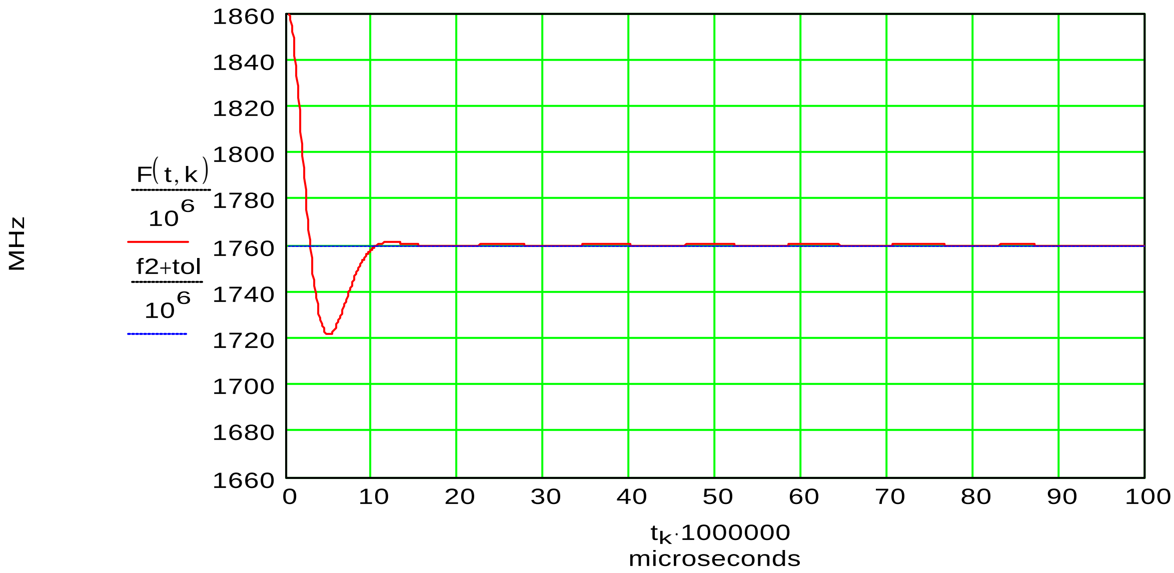
$$t_k := \frac{k}{10000000} \cdot sec \qquad F(t, k) := f2 + \sum_i A_i \cdot e^{(p_i \cdot t_k)} \cdot \left( \frac{1}{p_i} + R2 \cdot C2 \right)$$

$range := 100 \cdot 10^{(-6)} \cdot sec$ — 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




$span := 0.2 \cdot MHz$