Boost Charge Pump Current PLL

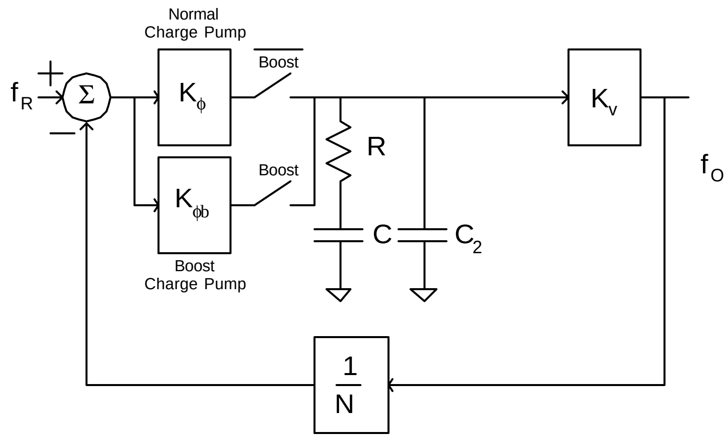

Fig. 2: 3rd-Order PLL with Current-Mode Phase-Detector and Boosted Charge Pump

- useful functions and identities
- Units
- Constants

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Introduction

In a boosted charge pump PLL, the loop dynamics are changed temporarily to increase the bandwidth of the PLL to allow faster settling. When the loop is close to settling, the bandwidth is reduced for good spurious and phase noise performance. There are several ways to boost the bandwidth, with the most popular method being an increase in the charge pump current. A boost in the charge pump current increases the unity-gain bandwidth, and changes the phase margin. For design an additional constraint must be introduced so the phase margin in boost and non-boost modes are a given value. The PLL need not be overconstrained, by adding to design procedure a new variable ωp/ωu, the ratio of the non-dominant pole to unity-gain bandwidth This is normally set equal to ωu/ωz, the ratio of the unity gain bandwidth to loop zero.

Inputs

$Boost := 10$ — Desired frequency boost

$f_{step} := 25MHz$ — Maximum output frequency step

$f_o := 1GHz$ — Output Frequency

$f_r := 1MHz$ — Reference frequency

$f_{acc} := 1kHz$ — Acceptable frequency error for settling

$PM_{des} := 60deg$ — Desired phase margin in non-boost mode

$PM_b := 50deg$ — Desired phase margin in boost mode

$I := 200\mu A$ — Charge pump current

$K_v := 2\cdot\pi\cdot 15\cdot\frac{MHz}{volt}$ — VCO Gain

$num := 100$ $\quad i := 1..num$ — Number of points for plotting

$f_u := 10kHz$ $\quad \omega_u := 2\cdot\pi\cdot f_u$ — Desired unity gain bandwidth

Preliminary Calculations

$N := \frac{f_o}{f_r}$ $\quad N = 1\times 10^3$ — Divider ratio

$K_\phi := \frac{I}{2\cdot\pi}$ — Tri-state charge pump gain

Pole and Zero Location Sizing

The open-loop transfer function for the PLL is

$$GH(s) = \frac{K_\phi \cdot K_v}{N \cdot (C_1 + C_2) \cdot s^2} \cdot \frac{wu\_wz \cdot \frac{s}{\omega_u} + 1}{1 + \frac{s}{\omega_u \cdot wp\_wu}}$$

Now by setting the loop gain equal to unity, the unity gain bandwidth and phase margin can be solved for with the result given in the following equations:

$$\omega_u = \sqrt{\frac{K_\phi \cdot K_v}{N \cdot (C_1 + C_2)} \cdot \sqrt{\frac{wu\_wz^2 + 1}{1 + \frac{1}{wp\_wu^2}}}} \qquad PM = atan(wu\_wz) - atan\left(\frac{1}{wp\_wu}\right)$$

In boost mode the bandwidths and phase margin equations become:

$$\omega_{ub} = \sqrt{\frac{K_{\phi b} \cdot K_v}{N \cdot (C_1 + C_2)} \cdot \sqrt{\frac{(wu\_wz \cdot B)^2 + 1}{1 + \left(\frac{B}{wp\_wu}\right)^2}}} \qquad PM_b = atan(wu\_wz \cdot B) - atan\left(\frac{B}{wp\_wu}\right)$$

Where B is the desired bandwidth boost in boost mode.

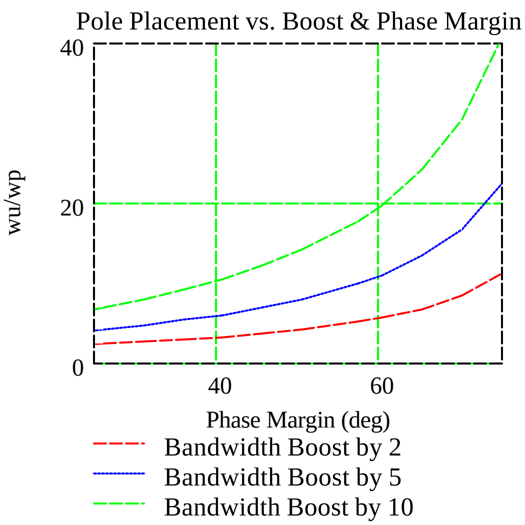
$$\omega_{ub} = B \cdot \omega_u$$

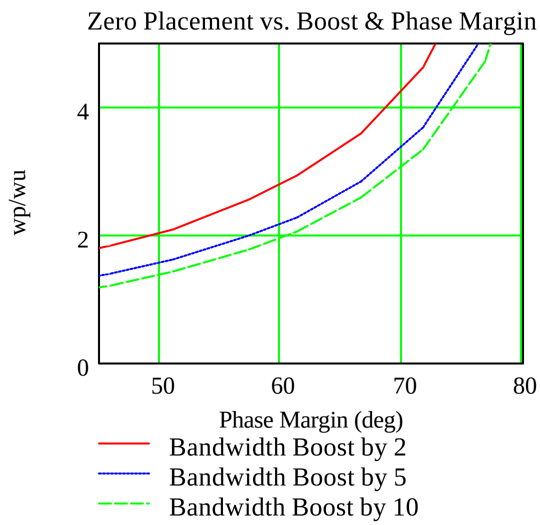
For design PM, PM_b, and B are given, which are used to find wu_wz and wp_wu with the following routine. x is a intial guess for the root finding routine.

$$\omega p\_\omega u(PM, PM_b, B) := \begin{array}{|l} x \leftarrow 3 \\ root\left(atan\left(tan\left(PM + atan\left(\frac{1}{x}\right)\right) \cdot B\right) - atan\left(\frac{B}{x}\right) - PM_b, x\right) \end{array}$$

$$\omega u\_\omega z(PM, PM_b, B) := tan\left(PM + atan\left(\frac{1}{\omega p\_\omega u(PM, PM_b, B)}\right)\right)$$

The following figures shows the effect of pole and zero spacings verses desired phase margin. Here the boost and the non-boost phase margins are swept together.





We can see the pole placement plots that the required zero placement is a weak function of the bandwidth boosting, but the pole placement is a strong function of the bandwidth boosting. A quick estimate the wu_wz and wp_wz values can be found by using the same value without boosting for wu_wz and use B times that value for wp_wz.

$$wu\_wz := \omega u\_\omega z(PM_{des}, PM_b, Boost) \qquad wu\_wz = 2.082$$

$$wp\_wu := \omega p\_\omega u(PM_{des}, PM_b, Boost) \qquad wp\_wu = 13.15$$

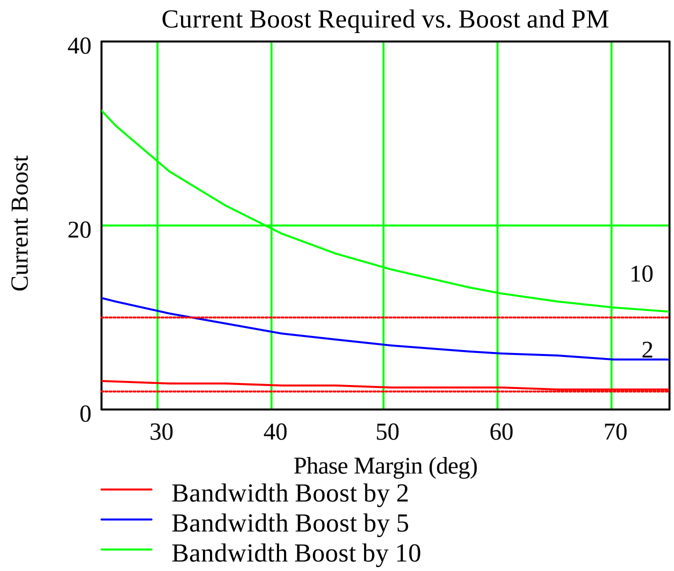
With a given B(bandwidth boost), and phase margins there is a required value for the boosted current. The following equation is the ratio of the boosted current to the un-boosted current.

$$K\phi b\_K\phi = B^2 \cdot \sqrt{\frac{wu\_wz^2 + 1}{1 + \frac{1}{wp\_wu^2}}} \cdot \sqrt{\frac{1 + \left(\frac{B}{wp\_wu}\right)^2}{(wu\_wz \cdot B)^2 + 1}}$$

As a function of the desired phase margins:

$$K\phi b\_K\phi(PM, PM_b, B) := B^2 \cdot \sqrt{\frac{\left(\omega u\_\omega z(PM, PM_b, B)^2 + 1\right) \cdot \left[1 + \left(\frac{B}{\omega p\_\omega u(PM, PM_b, B)}\right)^2\right]}{\left[\left(\omega u\_\omega z(PM, PM_b, B) \cdot B\right)^2 + 1\right] \cdot \left(1 + \frac{1}{\omega p\_\omega u(PM, PM_b, B)^2}\right)}}$$

We plot the current boost required for a given bandwidth boost in the next figure. An important concept to note is from the plot is that more current is required to boost the bandwidth than the ratio of the bandwidths. If a certain bandwidth is required for modulation or settling time purposes, care must be taken to overdesign the bandwidth to account for process variations, especially with respect to K_v of the VCO, which can vary up to 100%.



For large phase margins the boosted current approaches B, the bandwidth boost.

Finding Bandwidth Boost Given Current Boost

Alternatively, if the boosted current is given and the boosted bandwidth is calculated, a root finder can use the previous expression to find the resulting expression:

$$K\phi b\_K\phi_{given} := 10$$

$$B(PM_{des}, PM_b, K\phi b\_K\phi_{given}) := \begin{array}{|l} x \leftarrow 4 \\ root\left(K\phi b\_K\phi(PM_{des}, PM_b, x) - K\phi b\_K\phi_{given}, x\right) \end{array} \qquad B(PM_{des}, PM_b, K\phi b\_K\phi_{given}) = 7.378$$

Sizing the Loop Filter Components

With the pole/unity and zero/unity bandwidth ratios, the loop filter components can also be sized, by solving the following three equations simultaneously.

$$\omega_u = \sqrt{\frac{K_\phi \cdot K_v}{N \cdot (C_1 + C_2)} \cdot \sqrt{\frac{wu\_wz^2 + 1}{1 + \frac{1}{wp\_wu^2}}}}$$

$$\frac{\omega_u}{wu\_wz} = \frac{1}{R_1 \cdot (C_1 + C_2)}$$

$$\omega_u \cdot wp\_wu = \frac{1}{R_1 \cdot C_2}$$

The solution to these three equations are the following loop filter components:

$$C_{2B} := \frac{K_\phi \cdot K_v}{N \cdot wu\_wz \cdot \omega_u^2} \cdot \sqrt{\frac{wu\_wz^2 + 1}{wp\_wu^2 + 1}} \qquad C_{2B} = 63.92\,\mathrm{pF}$$

$$C_{1B} := \frac{K_\phi \cdot K_v \cdot (wp\_wu \cdot wu\_wz - 1)}{N \cdot wu\_wz \cdot \omega_u^2} \cdot \sqrt{\frac{wu\_wz^2 + 1}{wp\_wu^2 + 1}} \qquad C_{1B} = 1.686\,\mathrm{nF}$$

$$R_{1B} := \frac{N \cdot wu\_wz \cdot \omega_u}{wp\_wu \cdot K_\phi \cdot K_v} \cdot \sqrt{\frac{wp\_wu^2 + 1}{wu\_wz^2 + 1}} \qquad R_{1B} = 18.934\,\mathrm{k\Omega}$$

Plugging these values back into the original transfer function yields the following expression.

$$GH(s) = \sqrt{\frac{\frac{1}{wp\_wu^2} + 1}{wu\_wz^2 + 1}} \cdot \frac{1}{\left(\frac{s}{\omega_u}\right)^2} \cdot \frac{\left(wu\_wz \cdot \frac{s}{\omega_u} + 1\right)}{\left(1 + \frac{s}{\omega_u \cdot wp\_wu}\right)}$$

The magnitude and phase responses of this transfer function are

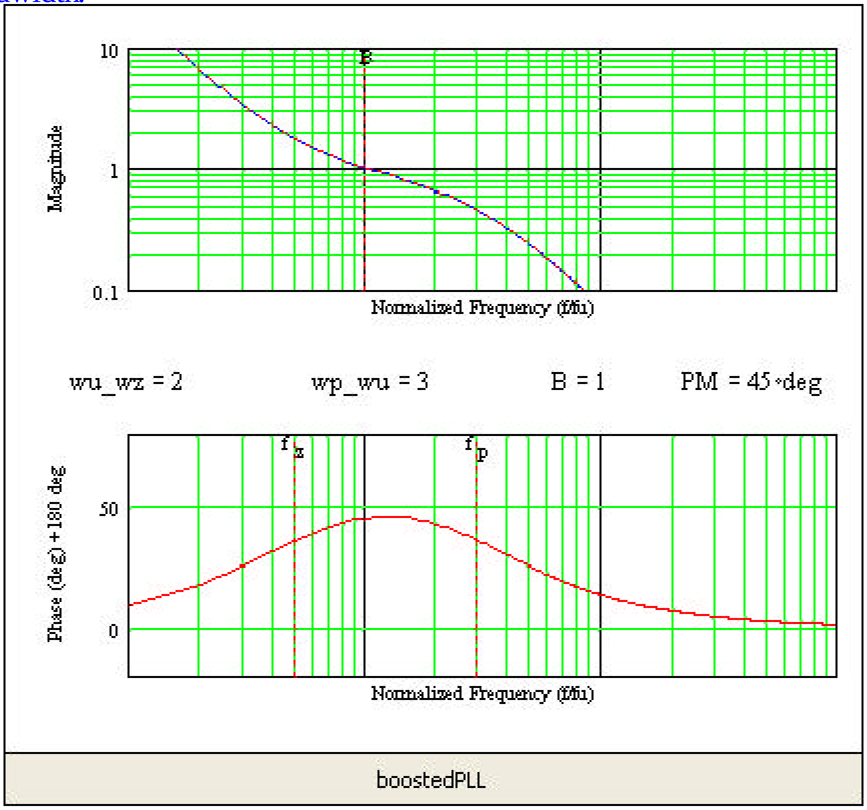
$$MagGH(f\_fu) := \sqrt{\frac{\frac{1}{wp\_wu^2} + 1}{wu\_wz^2 + 1}} \cdot \frac{1}{f\_fu^2} \cdot \sqrt{\frac{(wu\_wz \cdot f\_fu)^2 + 1}{1 + \left(\frac{f\_fu}{wp\_wu}\right)^2}}$$

and in boost mode

$$MagGHb(f\_fu) := \sqrt{\frac{\frac{1}{wp\_wu^2} + 1}{wu\_wz^2 + 1}} \cdot \frac{K\phi b\_K\phi}{f\_fu^2} \cdot \sqrt{\frac{(wu\_wz \cdot f\_fu)^2 + 1}{1 + \left(\frac{f\_fu}{wp\_wu}\right)^2}}$$

$$AngleGH(f\_fu) := -180deg + atan(wu\_wz \cdot f\_fu) - atan\left(\frac{f\_fu}{wp\_wu}\right)$$

The following movie illustrates how the poles, zeros and frequency response changes as the bandwidth boosting is changed. The zero location doesn't move that much with respect to boost to maintain stability at the low loop bandwidth. The pole location moves almost proportional to the boost and always remains a small factor larger than the boost bandwidth.



The closed loop expression for the PLL with boost filter in normal mode for frequencies much greater than the unity gain bandwidth is:

$$\left|fo\_fi\left(f_r\right)\right| = \sqrt{\frac{wp\_wu^2+1}{wu\_wz^2+1}} \cdot \frac{N}{\left(\frac{f_r}{f_u}\right)^2} \cdot wu\_wz$$

If we assume wp_wu=B*wu_wz, and $wu\_wz^2 >> 1$, the expression simplifies to

$$\left|fo\_fi\left(f_r\right)\right| = B \cdot \frac{N}{\left(\frac{f_r}{f_u}\right)^2} \cdot wu\_wz$$

Thus a boost in bandwidth is directly results in a loss of reference spur attenuation by the same amount. This means bandwidth in the unboosted mode will have be reduced by about sqrt(B), and on-chip capacitors also increased in area by the sqrt(B), so one must cautious using this architecture. In another article we see some loop filter modifications that can be made to improve stabilization in boost mode.
