PSS PNOISE vs. Transient Simulation for Dynamic Comparator

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Presentation Outline

1. PSS Setup

2. PNOISE Setup
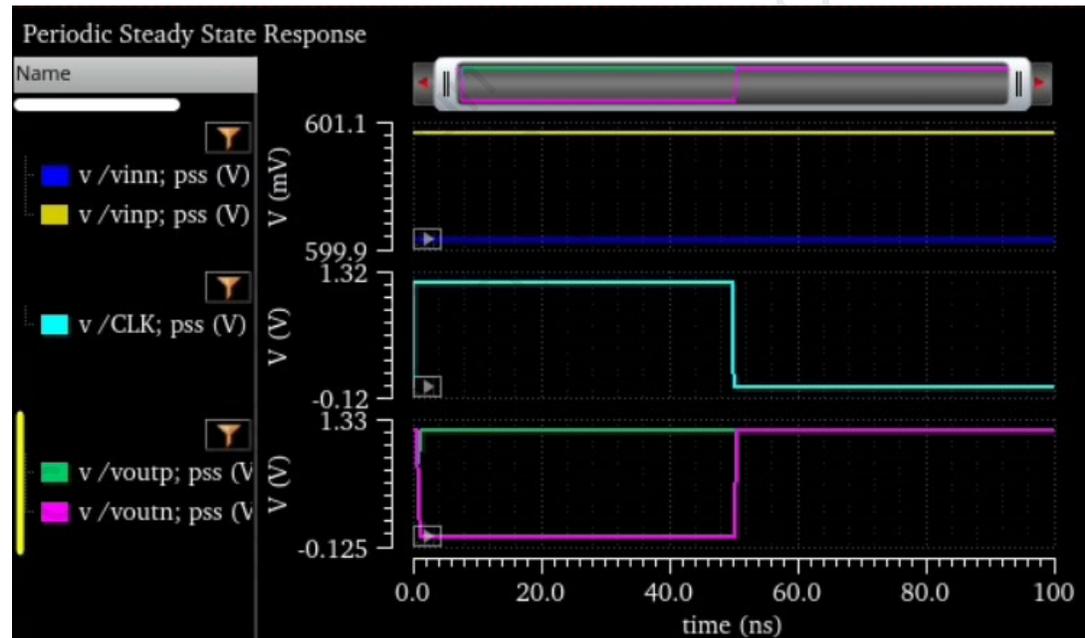
3. Dynamic Comparator Simulation

PSS Setup

PSS SETUP

- Steady State:

Periodic Steady State (PSS) Analysis

PSS is the equivalent of DC analysis but applied to periodic circuits: finds the periodic steady-state response of a circuit and evalutes the periodic operating point. The steady-state solution is then linearized for time-varying small-signal analysis as Periodic AC (PAC), Periodic Noise (PNOISE)…

PSS SETUP

- PSS Engine:

PSS SETUP

- ## PSS Engine:

  - ### Shooting Newton:

    - Try to solve iteratively: $v(0) - v(T) = 0$
    - It computes a transient simulation from 0 to T and compares all voltage and currents at the start and end of the shooting interval
    - It repeats for a second interval from T to 2T and so on, until it converges (or not…)
    - We can adjust the parameter tstab to skip the initial "start-up" behavior

Beat Period

V(0)   Error   V(T)
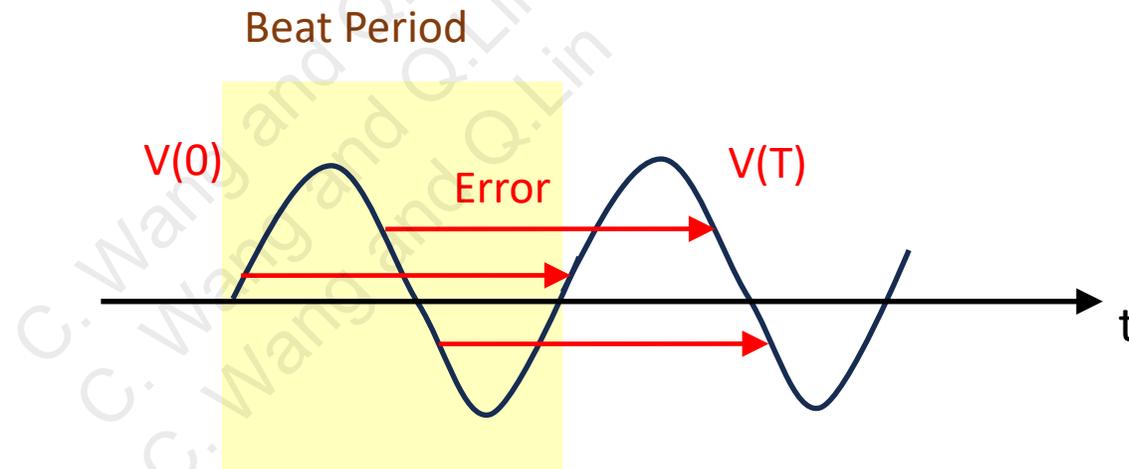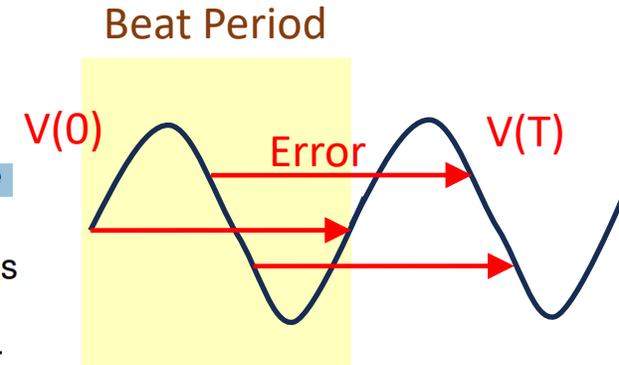
t

PSS SETUP

- **PSS Engine:**
  - Shooting Newton;

- Try to solve iteratively: $v(0) - v(T) = 0$
- It computes a transient simulation from 0 to T and compares all voltage and currents at the start and end of the shooting interval
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Beat Period

V(0)   Error   V(T)

1. Search Steady State:

```
pss: time = 130.6 ns    (2.56 %), step = 4 ns   Search (78.4 m%)
pss: time = 384.1 ns    (7.53 %), step = 4 ns   (78.4 m%)
                                        (large step)
Steady-state is detected after 400 ns.
```

2. Transient Simulation in Steady State

```
=============================
`pss': time = (300 ns -> 400 ns)   Beat Period
=============================
pss: time = 302.5 ns    (2.5 %),  step = 5 ps          (5 m%)
pss: time = 307.5 ns    (7.5 %),  step = 5 ps   Trans  (5 m%)
pss: time = 312.5 ns   (12.5 %),  step = 5 ps          (5 m%)
pss: time = 317.5 ns   (17.5 %),  step = 5 ps (small step) m%)
pss: time = 322.5 ns   (22.5 %),  step = 5 ps          (5 m%)
pss: time = 327.5 ns   (27.5 %),  step = 5 ps          (5 m%)
pss: time = 332.5 ns   (32.5 %),  step = 5 ps          (5 m%)
pss: time = 337.5 ns   (37.5 %),  step = 5 ps          (5 m%)
pss: time = 342.5 ns   (42.5 %),  step = 5 ps          (5 m%)
pss: time = 347.5 ns   (47.5 %),  step = 5 ps          (5 m%)
pss: time = 352.5 ns   (52.5 %),  step = 5 ps          (5 m%)
pss: time = 357.5 ns   (57.5 %),  step = 5 ps          (5 m%)
pss: time = 362.5 ns   (62.5 %),  step = 5 ps          (5 m%)
pss: time = 367.5 ns   (67.5 %),  step = 5 ps          (5 m%)
pss: time = 372.5 ns   (72.5 %),  step = 5 ps          (5 m%)
pss: time = 377.5 ns   (77.5 %),  step = 5 ps          (5 m%)
pss: time = 382.5 ns   (82.5 %),  step = 5 ps          (5 m%)
pss: time = 387.5 ns   (87.5 %),  step = 5 ps          (5 m%)
pss: time = 392.5 ns   (92.5 %),  step = 5 ps          (5 m%)
pss: time = 397.5 ns   (97.5 %),  step = 5 ps          (5 m%)
Conv norm = 641, max dI(V5:p) = 2.39401 uA, took 4.45 s.
```

```
Maximum value achieved for any signal of each quantity:
V: V(I8.CLKN) = 1.291 V    Error
I: I(V9:p) = 531.1 uA
Initial condition solution time: CPU = 1.658 ms, elapsed = 1.66392 ms.
pss: The steady-state solution was achieved in 3 iterations.
```
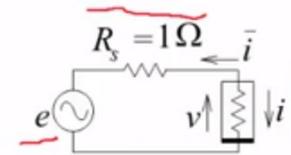
PSS SETUP

- ## PSS Engine:
  - ### Harmonic Balance:

- Steady-state solutions are approximated by finite Fouries series
- Frequency-domain linear analysis for the linear elements
- Time-domain analysis for non-linear elements, then transformed in the frequency domain
- Must solve system of K x N equations (K: number of harmonics in the Fourier series, N: number of nodes)

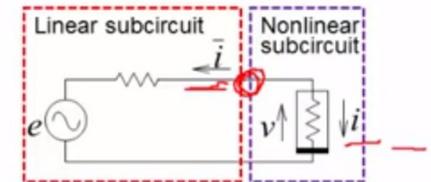– Assume that the signals in a circuit are a sum of sinusoids
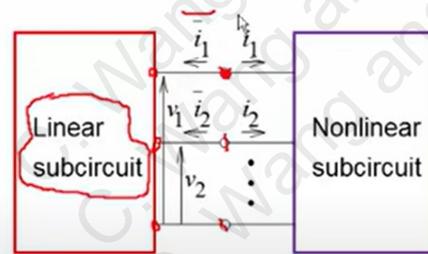
Example: HB Analysis 1/7

– Assume that the signals in a circuit are a sum of sinusoids

Trans Model $\quad i(t) = v(t) + [v(t)]^2$ $\qquad$ **Assumption**

$$v(t) = V_0 + V_1 \cos(\omega t) + V_2 \cos(2\omega t)$$

	Linear	Nonlinear
@DC:	$\bar{I}_0 = V_0$	$I_0 = V_0 + \frac{1}{2}V_2^2$
@w	$\bar{I}_1 = V_1 - E$	$I_1 = V_1$
@2w	$\bar{I}_2 = V_2$	$I_2 = \frac{1}{2}V_1^2$

Linear $\qquad$ **Nonlinear**

PSS SETUP

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```
================================
`pss': time = (1.1 us -> 1.2 us)
================================

    pss: time = 1.103 us   (2.51 %), step = 19.98 ps   (20 m%)
    pss: time = 1.108 us   (7.51 %), step = 19.98 ps   (20 m%)
    pss: time = 1.113 us   (12.5 %), step = 19.98 ps   (20 m%)
    pss: time = 1.118 us   (17.5 %), step = 19.98 ps   (20 m%)
    pss: time = 1.123 us   (22.5 %), step = 19.98 ps   (20 m%)
    pss: time = 1.128 us   (27.5 %), step = 19.98 ps   (20 m%)
    pss: time = 1.133 us   (32.5 %), step = 19.98 ps   (20 m%)
    pss: time = 1.138 us   (37.5 %), step = 19.98 ps   (20 m%)
    pss: time = 1.143 us   (42.5 %), step = 19.98 ps   (20 m%)
    pss: time = 1.148 us   (47.5 %), step = 19.98 ps   (20 m%)
    pss: time = 1.153 us   (52.5 %), step = 19.98 ps   (20 m%)
    pss: time = 1.158 us   (57.5 %), step = 19.98 ps   (20 m%)
    pss: time = 1.163 us   (62.5 %), step = 19.98 ps   (20 m%)
    pss: time = 1.168 us   (67.5 %), step = 19.98 ps   (20 m%)
    pss: time = 1.173 us   (72.5 %), step = 19.98 ps   (20 m%)
    pss: time = 1.178 us   (77.5 %), step = 19.98 ps   (20 m%)
    pss: time = 1.183 us   (82.5 %), step = 19.98 ps   (20 m%)
    pss: time = 1.188 us   (87.5 %), step = 19.98 ps   (20 m%)
    pss: time = 1.193 us   (92.5 %), step = 19.98 ps   (20 m%)
    pss: time = 1.198 us   (97.5 %), step = 19.98 ps   (20 m%)
```

```
********** initial residual **********
Resd Norm=1.34e+01  at node I8.I44.XIO_p1  harm=(1000)

********** iter = 1 **********
Delta Norm=5.16e-01  at node V8:p  harm=(1000)
Resd Norm=1.14e+00  at node I8.net1  harm=(999)

********** iter = 2 **********
Delta Norm=2.05e-02  at node V8:p  harm=(1000)
Resd Norm=8.48e-01  at node I8.net1  harm=(999)

********** iter = 3 **********
Delta Norm=4.81e-02  at node net3  harm=(0)
Resd Norm=2.04e-01  at node net4  harm=(416)

********** iter = 4 **********
Delta Norm=1.93e-02  at node net3  harm=(0)
Resd Norm=2.56e-02  at node I8.net1  harm=(1000)

********** iter = 5 **********
Delta Norm=1.57e-02  at node net3  harm=(0)
Resd Norm=5.35e-03  at node I8.net1  harm=(78)

********** iter = 6 **********
Delta Norm=9.37e-04  at node net3  harm=(0)
Resd Norm=2.01e-03  at node I8.net1  harm=(52)
```

PSS SETUP

- PSS Engine:
  - Shooting Newton vs. Harmonics Balance

Use shooting Newton for:

- Circuits where input signals have sharp transitions
- Strongly nonlinear circuits
  - Frequency dividers
  - Strongly-nonlinear resonatorless oscillators, such as
  -
    - Ring oscillators,
    - Relaxation oscillators,
    - Oscillators containing digital control components,
    - Oscillators with dividers.

Use harmonic balance for:

- High dynamic range, weakly-nonlinear systems
  - RF front-ends (LNA, Mixer)
  - IQ modulators
- Mildly nonlinear oscillators with resonators, such as
  - LC oscillators
  - Crystal oscillators
  - Negative-gain oscillators
- Circuits with distributed components
  - Transmission lines
  - S-parameter models

PSS SETUP

- PSS Engine:

Andrew Beckett
over 12 years ago

It depends on whether you're using shooting or harmonic balance. From your description above, it sounds like shooting.

The main reason is if you actually want to observe the harmonics produced by PSS. That is useful in itself in some cases. If you're only doing the PSS as a means to get a steady state (it's not a "DC operating point") in order to do a small signal analysis (e.g. pnoise, pac, pxf etc), then you don't have to save any harmonics. maxacfreq would be sufficient (assuming you even need to set that; maxacfreq defaults to 4x the highest harmonic requested, or 40x the PSS fundamental, whichever is the higher). So you can generally consider the maxharms to be the number of output harmonics.

For Harmonic Balance however it affects the accuracy - it's quite different.

The SpectreRF Theory document will probably describe this in more detail (I didn't check the documentation to make sure or point you in the right place due to lack of time right now).

Andrew.
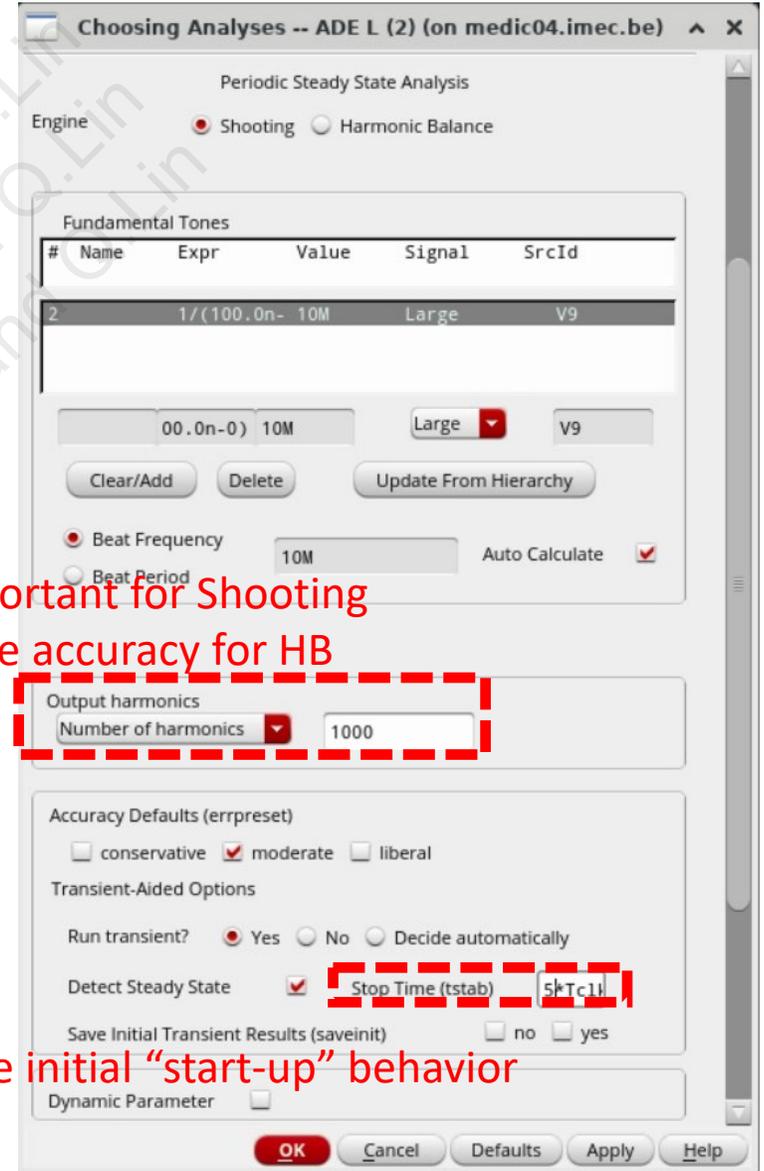
Not Important for Shooting
Influence accuracy for HB

skip the initial "start-up" behavior

PNOISE Setup

PNOISE SETUP

- PNOISE: (Small signal analysis)

Noise-folding by intermodulation

$$S_{VOA}(f) = A^2 S_{Vn}(f)$$

Input spectrum

$$S_{Vdm}(f)$$

Spectrum after modulation

$$S_{vout}(f) = A^2 \sum_{k=-\infty}^{\infty} |C_k|^2 S_{BB} = A^2 S_{BB}$$
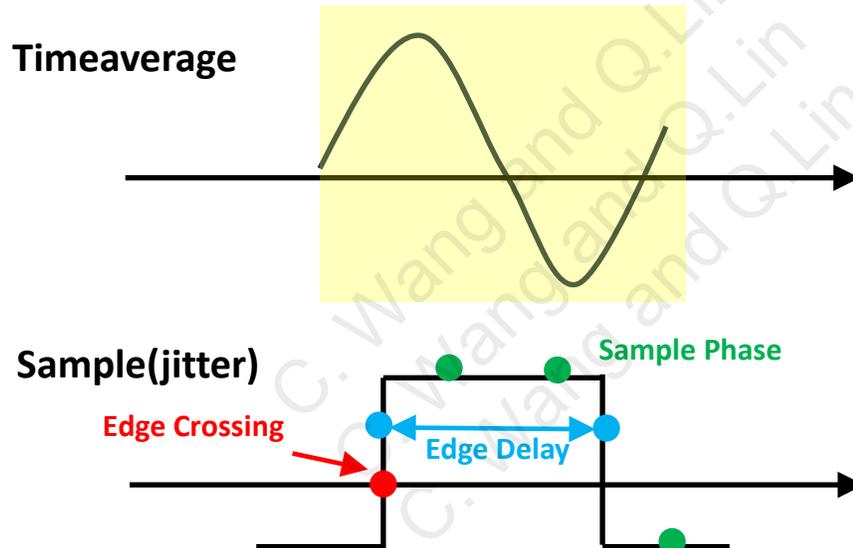
Noise Spectrum range:

Influence accuracy by noise-folding:
Change with maxacfreq in PSS together

PNOISE SETUP

- PNOISE: (Small signal analysis)

In noise analyses it is important to set the *maxsideband* parameter to accurately account for noise folding. Setting it too low results in a systematic underestimation of the noise whereas setting it to high results in excessively long simulations. The best approach to setting the *maxsideband* parameter is to increase it until the noise results stabilize, then back off a bit to achieve an acceptable level of accuracy. Once *maxsideband* is set, go back to the PSS analysis and make sure *maxacfreq* is set accordingly. (§2.2)

FIGURE 4 $S_c(f)$, as computed with analysis unsmpledNoise in Listing 1 with *various values of maxsideband*.

Increased maxsideband

Reduced error
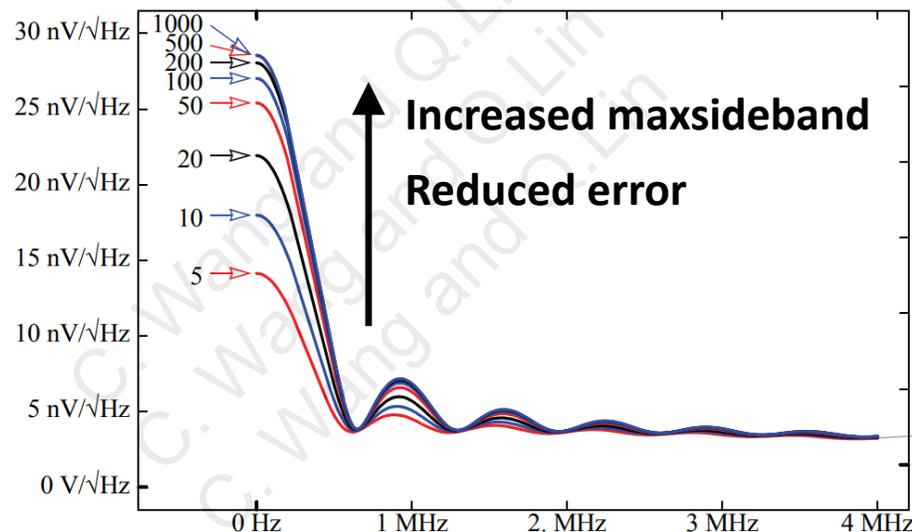
Noise Spectrum range:

Sweeptype   default   Sweep is currently absolute

Output Frequency Sweep Range (Hz)

Start-Stop   Start   1k   Stop   Fc1k/2

Stop At Half Fundamental Frequency   no   yes

Sweep Type

Automatic

Add Specific Points

Add Points By File

Sidebands

Method   ⦿ default   ◯ fullspectrum

Maximum sideband   1000

When using shooting engine, default value is 7.

Influence accuracy by noise-folding:
Change with maxacfreq in PSS together

PNOISE SETUP

- PNOISE: (Small signal analysis)

Timeaverage: measures the **average noise at all time points** in the PSS fundamental (1 cycle).

Sample(jitter): For **circuits with sharp transition** edges. Sampled pnoise measures the **noise power at a specific event** (time point on the waveform).

Timeaverage

Sample(jitter)

Sample Phase

Edge Crossing

Edge Delay

PNOISE SETUP

- PNOISE: (Small signal analysis)

Timeaverage: measures the **average noise at all time points** in the PSS fundamental (1 cycle).

Sample(jitter): For **circuits with sharp transition** edges. Sampled pnoise measures the **noise power at a specific event** (time point on the waveform).

Timeaverage

Sample(jitter)

Edge Crossing

Edge Delay

Sample Phase

Dynamic Comparator Simulation

TRANSIENT SIMULATION

- Testbench

Sweep small input dc difference
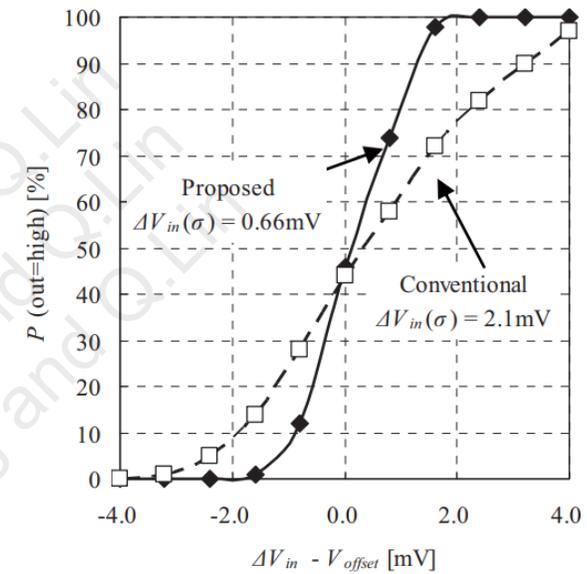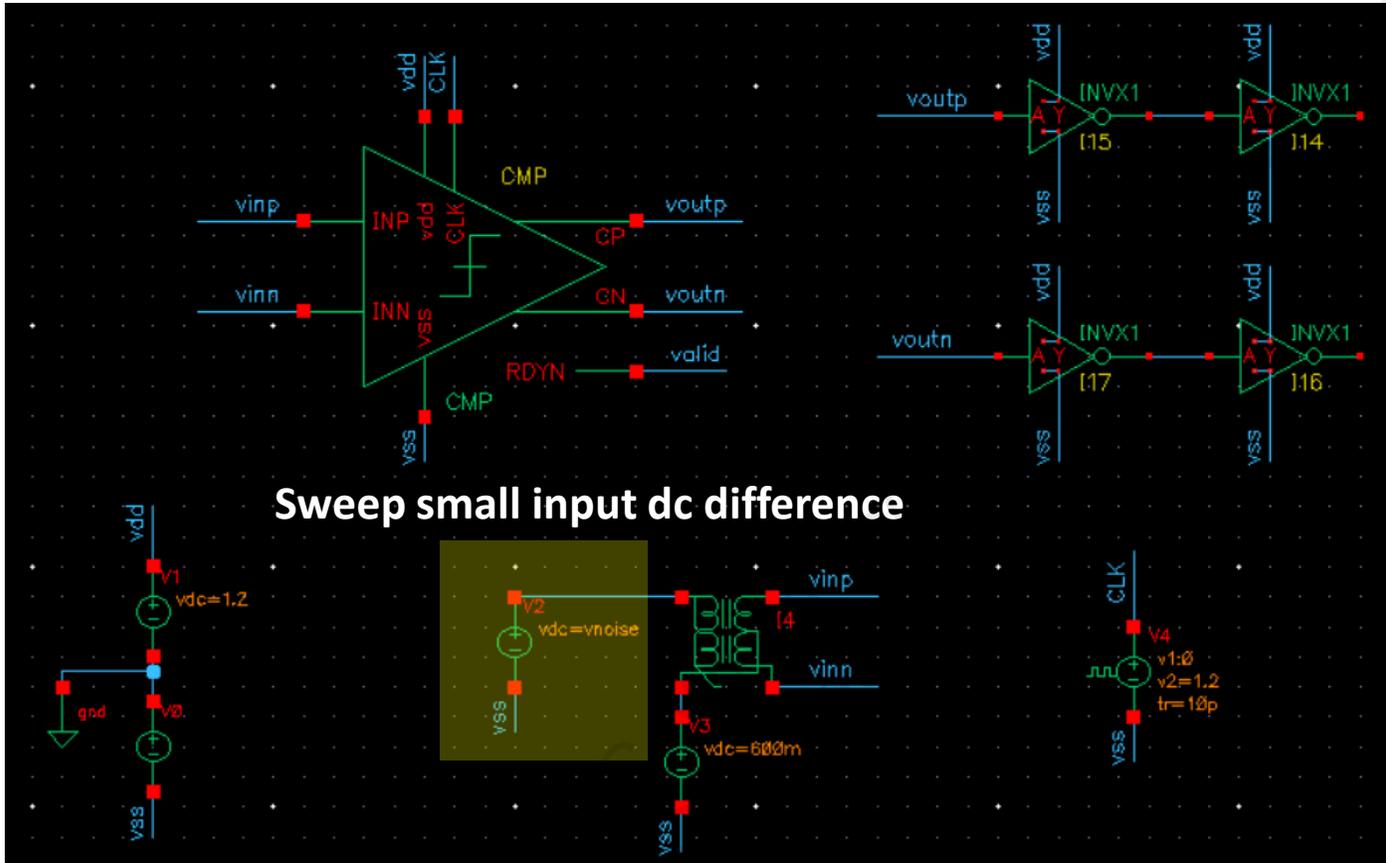
Parameters: vnoise=228.9u					
2	SAR_ADC_TB_CM...	v /vinp; tran (V)	📈		
2	SAR_ADC_TB_CM...	v /vinn; tran (V)	📈		
2	SAR_ADC_TB_CM...	/voutp	📈		
2	SAR_ADC_TB_CM...	/I0/vdd	📈		
2	SAR_ADC_TB_CM...	Current		4.18u	< 5u
2	SAR_ADC_TB_CM...	Distribution		838.8m	> 0.84
2	SAR_ADC_TB_CM...	Valid	📈		
Parameters: vnoise=237.8u					
3	SAR_ADC_TB_CM...	v /vinp; tran (V)	📈		
3	SAR_ADC_TB_CM...	v /vinn; tran (V)	📈		
3	SAR_ADC_TB_CM...	/voutp	📈		
3	SAR_ADC_TB_CM...	/I0/vdd	📈		
3	SAR_ADC_TB_CM...	Current		4.168u	< 5u
3	SAR_ADC_TB_CM...	Distribution		850.9m	> 0.84
3	SAR_ADC_TB_CM...	Valid	📈		

Input referred noise: 240uV
Simulation Time: >70 min

PSS PNOISE SIMULATION

- Testbench

Set input dc difference 1mV
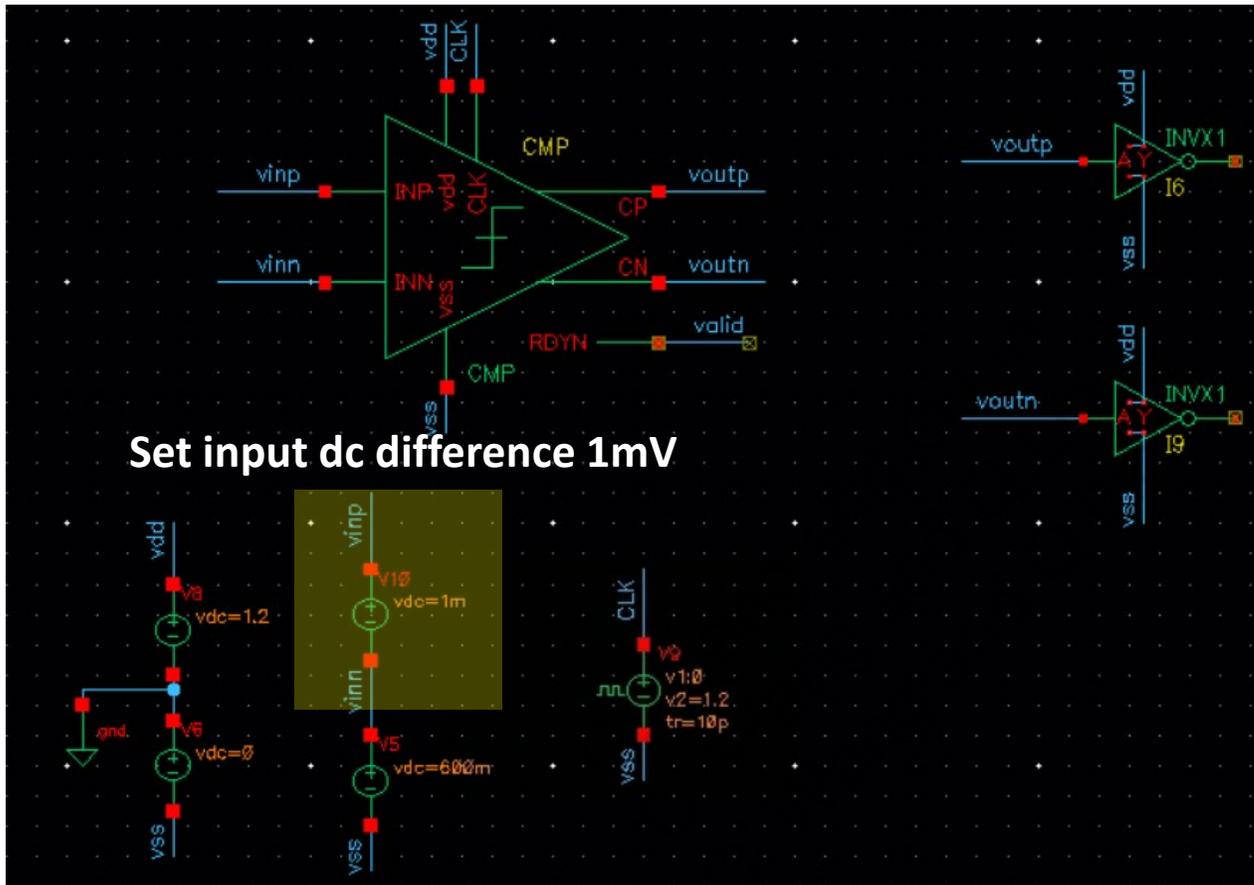
3.3 Dynamic Comparator Noise Characterization

Periodic noise analysis can be used to measure the noise of a dynamic comparator. Periodic noise is a small signal analysis performed after the periodic steady-state has been calculated using Spectre RF shooting Newton periodic steady-state analysis. The difference between pnoise and traditional noise analysis is that, pnoise includes the effect of noise folding, noise aliasing from out of band into the band of interest. The methodology for calculating the comparator noise is

1. Apply a small DC input voltage to comparator (1mV differential) and clock the comparator

2. Setup Shooting Newton analysis to calculate the periodic operating point

3. Use sample periodic noise analysis with the sample point determined by the differential output levels (internal latching nodes) of the comparator

4. Set the sampling point to where the comparator differential output levels are separated by about 50mV

5. Integrate squared noise of sampler output and take square root to find rms noise on ideal sampler from DC to Nyquist frequency

6. Divide noise by gain from input to sampler output (50mV/1mV)

PSS PNOISE SIMULATION

• Testbench

Edge Crossing:
    Output referred noise: 11,526mV
Edge Delay:
    Output referred noise: 11,53mV
Gain = 50
Input referred noise: 231uV
Simulation time: 5min

THANKS