Analogue Design

A Proportional to Temperature Current Source
(PTAT)
Tutorial

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Overview

This tutorial describes the essentials of the design of a Proportional To Absolute Temperature (PTAT) current source.

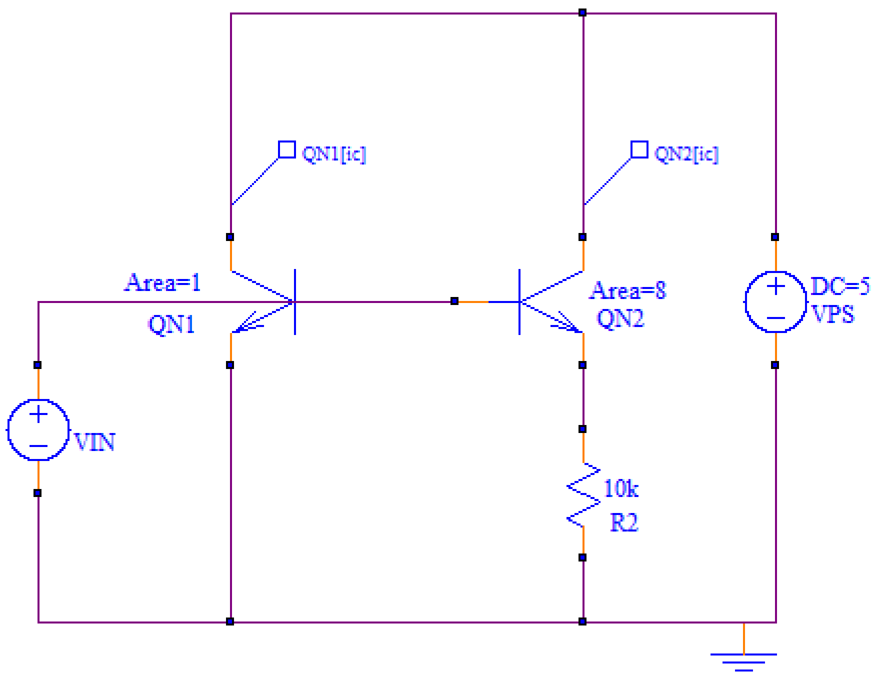
A PTAT current generator is an inherent core topology in the design of "Bandgap" voltage references. Typically, a positive slope with temperature PTAT current is passed through a resistor to generate a PTAT voltage that is added to a negative with temperature slope PTAT voltage. The negative slope PTAT usually being the Vbe of a diode, or diode connected transistor. This summed voltage is so arranged so that the individual PTAT cancel each other and result in a nominally zero variation of voltage with temperature output voltage.

Delta V_{be} Source

The starting point of the PTAT generator is a topology referred to as a delta-V_{be} current source.

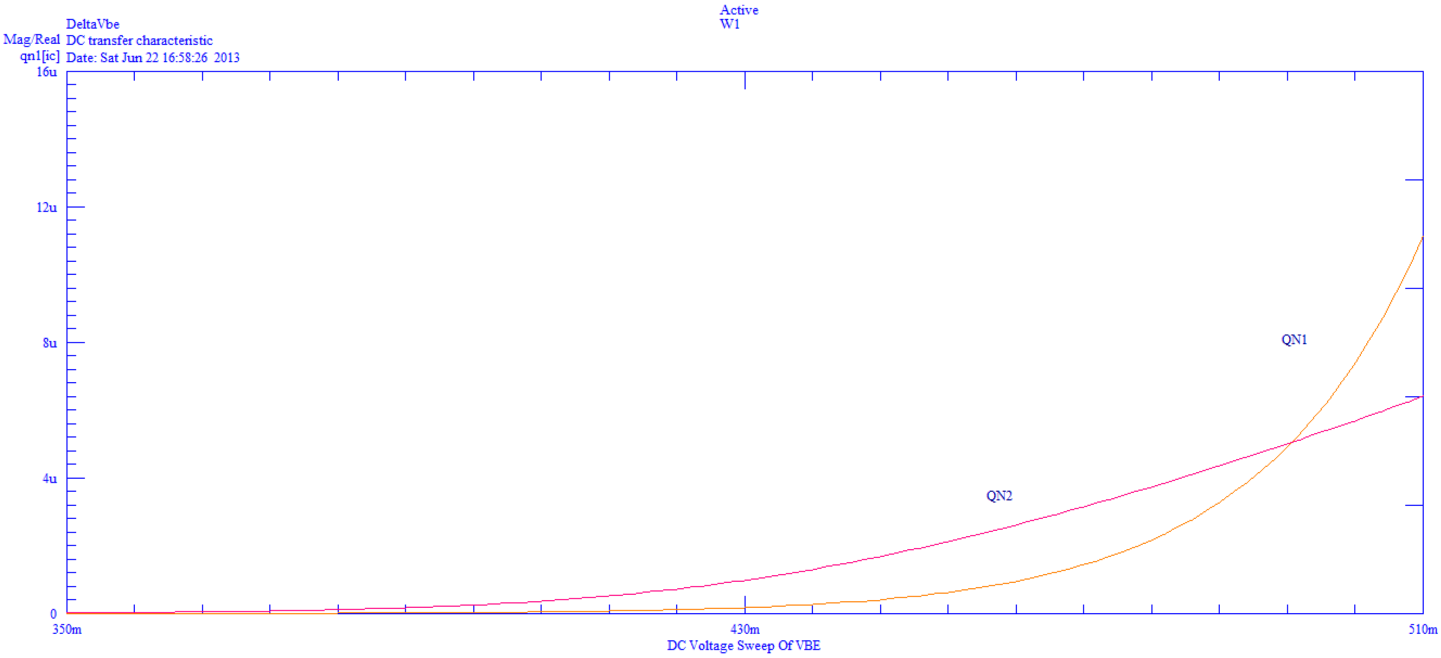
Consider the following circuit with a voltage source, VIN, swept from 0v to some final voltage:

Fig. 1



For small VIN voltages, the currents are low, such that there is a negligible voltage drop across R2. QN2 is chosen to have a much larger area than QN1, so QN2's current will be larger than the current of QN1, and initially increase exponentially at a much faster rate than the current of QN1 as VIN is increased. However, in the limit of large VBE voltages, R2 will limit QN2's current to the order of VIN less than about 0.7V divided by R2. In contrast, the current of QN1, will keep increasing exponentially. This results in the following type of graphs for the currents of QN1 and QN2.

Fig. 2

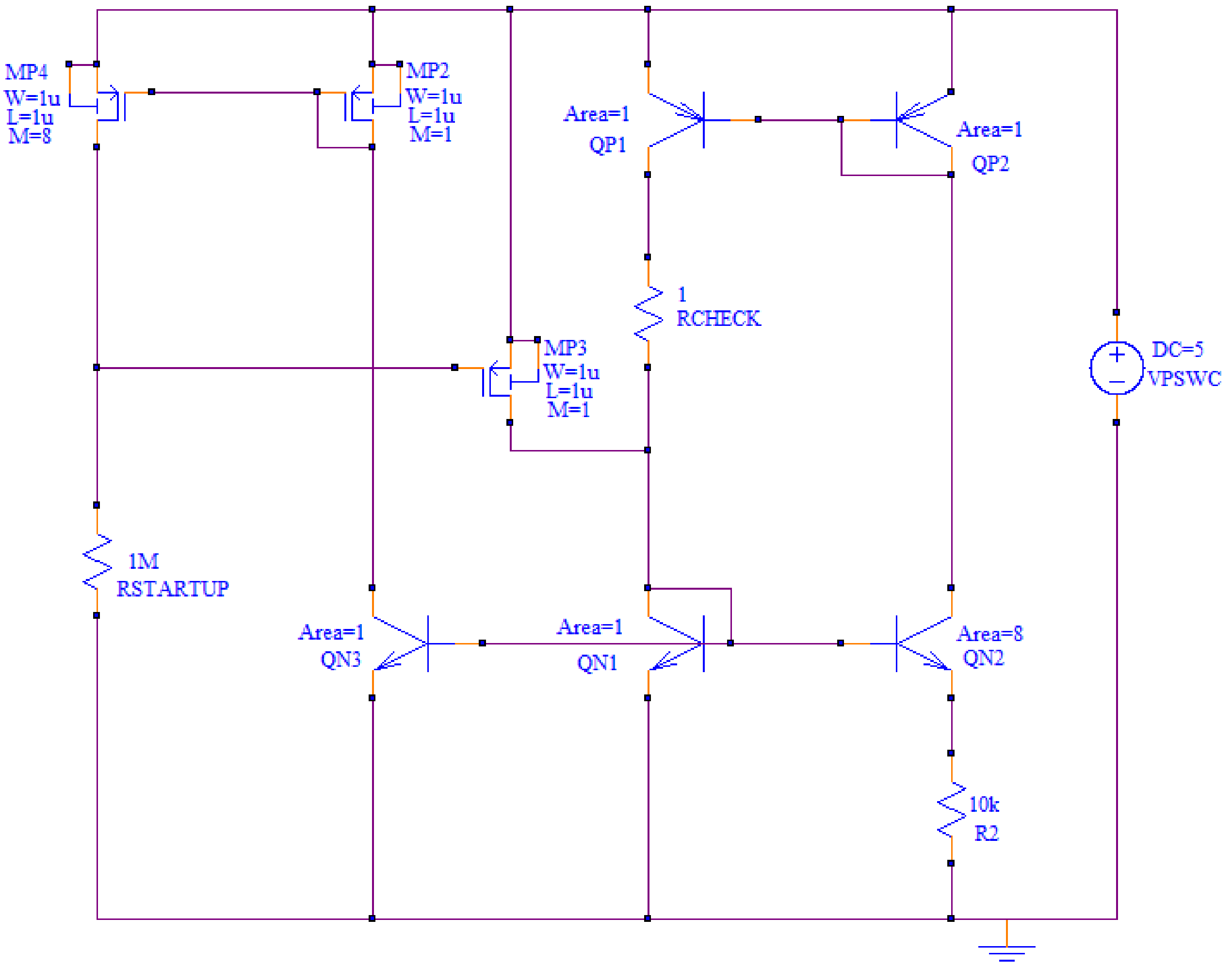


It can be seen from the graph, that there is an intersection of the currents of QN1 and QN2. That is, there are two points where the currents of QN1 and QN2 are equal. One point is at zero VIN, being zero current in both transistors, the second point being at a “special” equality point.

PTAT Generator

Consider the following circuit where the collectors of QN1 and QN2 are connected by a current mirror.

Fig. 3



First assume that MP3 is non conducting. Transistors QN1, QN2, QP1 and QP2 can then be seen to operate in what is apparently a DC positive feedback loop. That is, if there is a small current in QN2's collector, it will produce a current in QP1's collector, which in turn will produce a current back in QN2 due to the voltage dropped across the V_{be} of QN1. However, if such a current in QN2 attempted to become larger than QN1 after the intersection point shown in Fig 1. , such a condition would then try and force a current back in Q1 that is equal to QN2 because of the current mirror. Thus, it can be seen that any departure from the equality current point, such a departure would act in a way to reduce that departure. Such a loop is a negative feedback loop in the sense of holding the DC current values to a stable operating point.

If there is initially zero current in QN1, then there would be zero current in QN2, which by virtue of the current mirror, it would dictate zero current back in QN1. This would also be stable condition of zero currents, but one that is not desired. However, if there were no current in QN1, QN3 would also be off, such that RSTARTUP would then be able to turn on MP3 to force current into QN1. The MP3 current will therefore initiate the start-up of the Q1 and Q2 loop. When QN1 has sufficient current, this current will mirror to MP4 and turn off the MP3 start-up current. With suitable design, it can be arranged that the start-up loop will always start-up the Q1 QN2 loop and turn off when that loop is operating correctly.

Operating Point v Temperature

The collector/emitter current in a transistor can be shown to be related to its base emitter voltage as:

$$I_c = I_s(T)(e^{\frac{V_{be}}{V_t}} -1)$$

$$\text{where } V_t = \frac{q}{KT}$$

Or, neglecting the 1 for $V_{be} >> 0$:

$$I_c = I_s(T)\, e^{\frac{V_{be}}{V_t}}$$

From inspection of the schematic Fig. 1, the currents in QN1 and QN2 can therefore be expressed as:

$$I_{cqn1} = I_s\, e^{\frac{Vin}{V_t}}, I_{cqn2} = A_r I_s\, e^{\frac{Vin - I_{cqn2}R}{V_t}}$$

$$I_{cqn1} = \frac{I_{cqn2}}{A_r} e^{\frac{I_{cqn2}R}{V_t}}$$ and see for example, [Widlar Current Source]

A_r being the relative ratio of transistor emitter areas.

At the stable intersection point, the currents are equal such that:

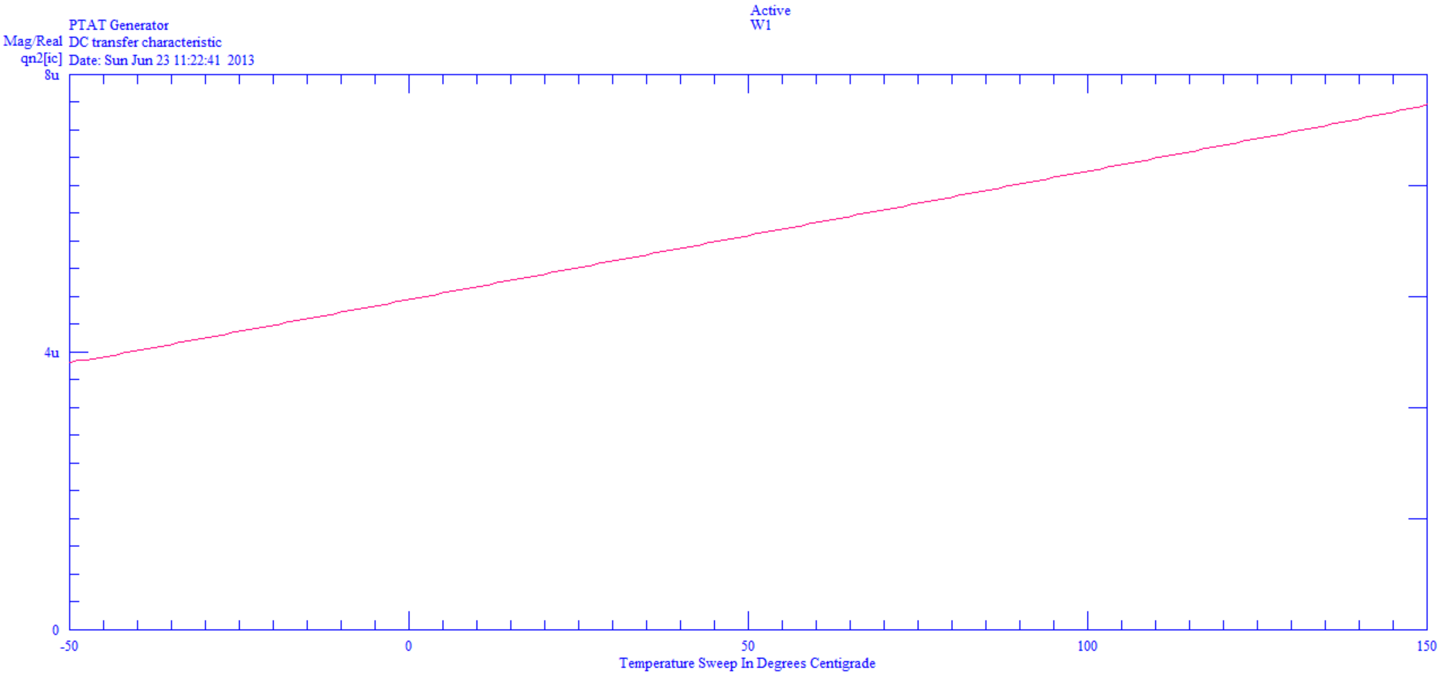
$$A_r = e^{\frac{I_{cqn2}R}{V_t}}$$

$$I_{cqn2} = \frac{V_t}{R}\ln(A_r) = \frac{\Delta V_{be}}{R}$$

$$I_{cqn2} = \frac{KT}{Rq}\ln(A_r)$$

Thus, there is a linearly increasing current in QN1 and QN2 with respect to temperature. This current is referred to as a PTAT current.

Fig. 4



Start-up Design Procedure

The start-up circuit needs to reliably start the PTAT loop yet turn off once the PTAT loop is started. In general, this is a straightforward procedure with modern design simulation tools. However, it should be appreciated that, in principle, as there is more than one numerical solution to the equations of the circuit, SPICE might well find the one you want without the start-up circuit actually being responsible. That is, the start-up circuit might be faulty, but it is not apparent from the simulations! Fortunately, the simulation results themselves can be used to effectively prove that the start-up circuit must work.

The basic principals are:

A Ensure that the minimum current in QN1, over all operating conditions in its valid loop state, will force enough current in MP4 to fully turn off MP3.

B That the start-up generates enough current to force the PTAT loop to start. That is, overcomes potential losses such as very low current gain at low currents.

C Leakages (e.g. at high temperatures) do not keep the start-up circuit either on (MP3) when it should be off, or off (MP4) when it should be on.

D ***NEVER*** use start-up circuits that are dynamic (e.g. caps) or relies on leakages (e.g. diodes).

There are many ways to implement a start-up circuit. The method used here is just an example. Some may be easier to check for reliability, but may have other blemishes.

Design

Determine the minimum $I_{cqn2} \sim \dfrac{\Delta V_{be}}{R_{\max}}$

Determine the maximum $I_{startup} \sim \dfrac{VPS_{\max}}{R_{\min}}$

Tests

1 Run VPS DC and Slow VPS TRAN sweeps over all process corners and temperatures.

2 Run Temperature sweeps over all process corners and DC VPS values.

3 Check minimum current of QN1 multiplied by its transfer ratio to MP4 sinks the max current of RSTARTUP by a factor of two to four. This will guarantee that MP3 is off when the bandgap is started. This ratio is kept large enough, but not so large that MP3 is always shunted off by MP4 leakage and otherwise fail to start bandgap.

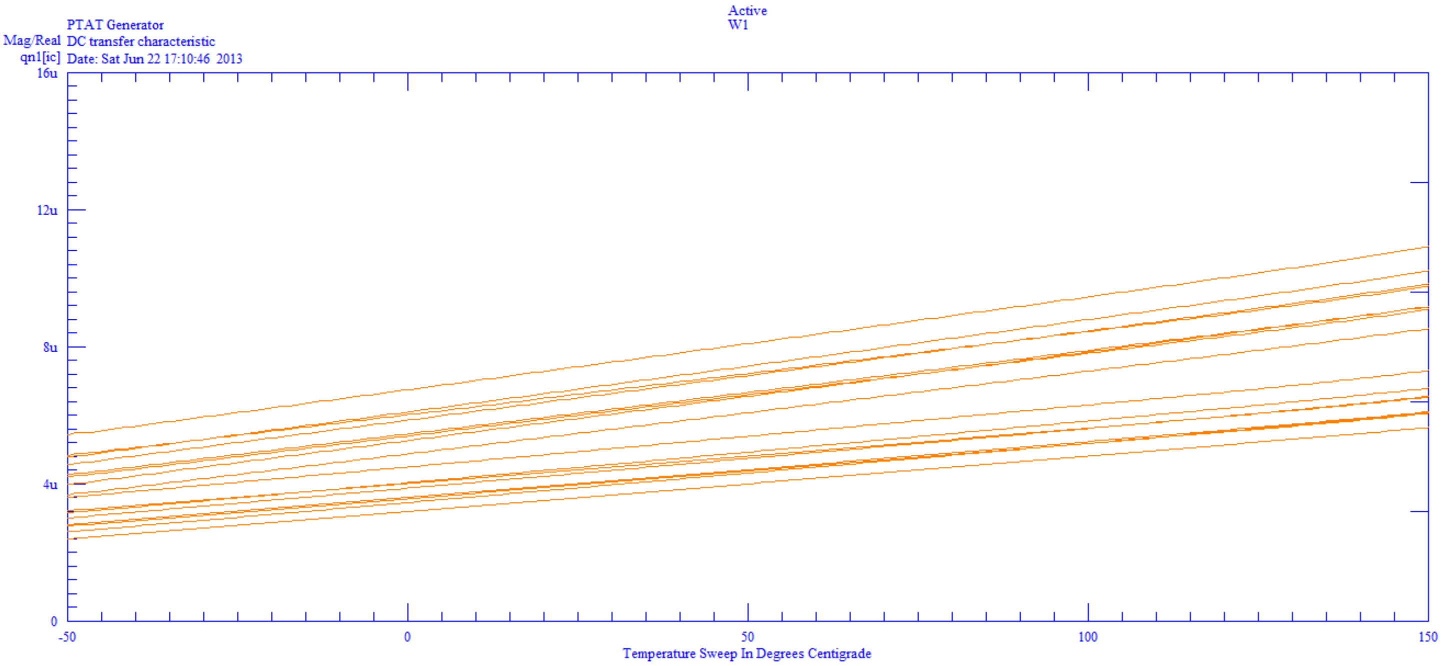
4 Check that the leakage from MP3 is minimal.

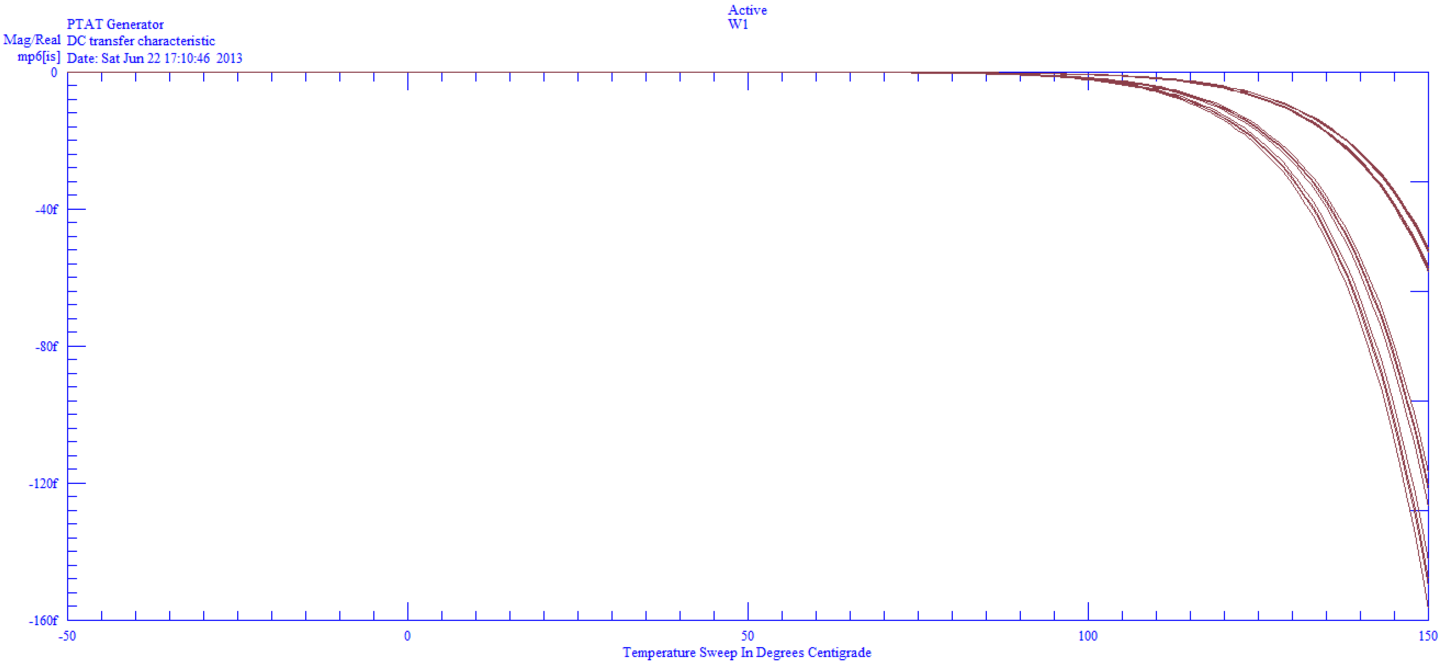
5 Check that there are no start-up limit cycle oscillations of the start-up loop on transient power ups (rare), compensate if required. A capacitor to supply/ground at the resistor node is usually sufficient.

7 To check.

Set RCHECK to a very high value. Run the above corners again. MP3 now forms a negative feedback loop and will now set the V_{be} voltage node. Check that the max current in QN1 is always less than its minimum when QN1 is connected normally. This proves that the start-up loop cannot force a third stable state. The check here is to ensure that the start-up loop can not hold the circuit at a higher current than that set by the PTAT loop. The PTAT loop will still force this current to go higher when re-connected, and by the above, shut off QP3.

Sample WC Process Corner Runs





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