Performance verification of start-up circuits in reference generators

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Abstract — **A new approach for identifying the number of stable equilibrium points in supply-insensitive bias generators, references, and temperature sensors based upon self-stabilized feedback loops is introduced. This provides a simple and practical method for determining if these circuits require a "start-up" circuit and, if needed, for verifying that the startup circuit is effective at eliminating undesired stable equilibrium points in the presence of process and temperature variations. This approach is demonstrated by considering the well-recognized inverse Widlar bias generator/temperature sensor as an example.**

Keywords :start-up circuit, equilibrium points, references, bias generators

I. INTRODUCTION

Bias generators, references, and temperature sensors (BRT) are often built with a self-stabilizing feedback loop that inherently provides a low sensitivity of the output to variations in the supply voltage. Although a rigorous analytical characterization of the self-stabilizing feedback loop is seldom discussed in the circuit design community, most designers recognize that these circuits often require a "start-up" circuit to force these circuits to operate in the desired state and these start-up circuits are invariable included as part of the design.

The use of the term "start-up" circuit as a method for overcoming an inherent limitation in these self-stabilized loops is not particularly descriptive of the problem the "start-up" circuits are solving. Specifically, many of the more popular self-stabilizing feedback loops that are used for BRT applications have more than one stable operating point and the start-up circuits are used to eliminate the undesired stable operating points from the circuit.

Some results on the design of ultra-small, high-accuracy on-chip threshold-based temperature sensors for power/thermal management in multi-core systems based upon a supply-insensitive self-stabilizing feedback loop have been recently reported [1-3] along with methods for guaranteeing that these circuits have a single stable equilibrium point. Others have focused specifically on the design of better start-up circuits [4-7].

A standard practice in industry for verifying that a start-up circuit is effective is to run repeated transient simulations to verify that the BRT circuit "starts up" correctly, that is, to verify that the circuit operates as desired within an acceptable delay from the time the transient analysis starts. Although this approach often results in start-up circuits that serve the intended purpose, it does not guarantee that all undesired stable equilibrium points have been eliminated. And, if all undesired stable equilibrium points have not been eliminated, an unanticipated sequence of transient events during normal operation can cause the circuit to move to an undesired stable equilibrium point. And even if the undesired stable equilibrium points have been eliminated for the conditions specified in the transient simulation, process and temperature variations may cause an undesired stable equilibrium point to reappear.

In this work, a simple and efficient method is proposed for verifying that a BRT circuit based upon a self-stabilizing feedback loop has a single stable equilibrium point. And, if this method shows the existence of one or more undesired stable equilibrium points, the method can be used again for verifying that circuit modifications (e.g. adding a "start-up" circuit) that are made to eliminate undesired stable equilibrium points are effective at their removal

The overall challenges associated with multiple stable equilibrium points are discussed in Section II. The analysis on how the proposed method works is explained in Section III. Section IV gives the design and simulation examples to demonstrate this approach. A summary of this work is presented in Section V.

II. START–UP ISSUE

Simulation of a circuit to verify whether a start-up circuit is needed or whether a start-up circuit is robust can be challenging. Designers usually assume that a start-up circuit is not needed if simulations of the reference circuit, either static or transient, do not show the existence of a second stable operating point. If simulations do not show the existence of a second stable operating point, it is often concluded that the reference circuit always works appropriately. Furthermore, if any simulation of the reference circuit shows the existence of an undesired stable operating point, it is tempting for the designer to add a start-up circuit and observe that the undesired stable operating point disappeared when the simulation is repeated. But, since any simulator will only provide one solution to a circuit, there is no assurance that if simulations of

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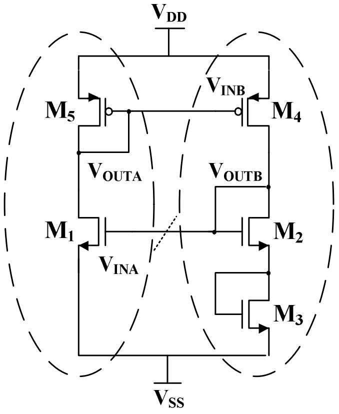

Figure 1 Inverse Widlar Structure

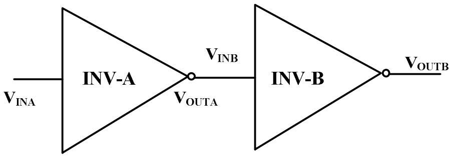

Figure 2 Broken inverter loop

the reference do not present an undesired stable operating point that such a point does not exist. Actually, the designer may be really unlucky if simulations of a circuit with two stable equilibrium points always resulted in the desired stable operating point as these simulations would mask the presence of the undesirable stable operating point.

III. PROPOSED START-UP ANALYSIS METHOD

A. *Transfer Characteristic of the bias generator*

In this section, BRT circuits with multiple stable equilibrium points are discussed. As an example, we will first consider the inverse Widlar bias generator and will generalize the results to other BRT circuits.

The inverse Widlar generator is shown in the Figure 1 and can be viewed as two cross-coupling inverters that form a self-stabilized feedback loop. The inverter on the left comprised of M_1 and M_5 is a common-source (CS) amplifier with input on the gate of M_1 and with a diode-connected load. The circuit on the right side comprised of M_4, M_2, and M_3 is also a CS amplifier with input on the gate of M_4 but with two series diode-connected devices serving as the load. Since the dc input impedance on each of the inverters is infinite, there is no dc loading on the output of either inverter.

Since there is no dc loading, the static loop gain can be obtained by breaking the loop either at the input of M_1 or the input of M_4 to obtain a two-inverter cascade. If the loop is broken at the input of M_1, we obtain the cascade shown in Figure 2. Analytical expressions for the transfer characteristics of the two-inverter cascade can be readily obtained. Assuming a square-law device model is adequate, it follows that the output V_{OUTA} is given by (1)

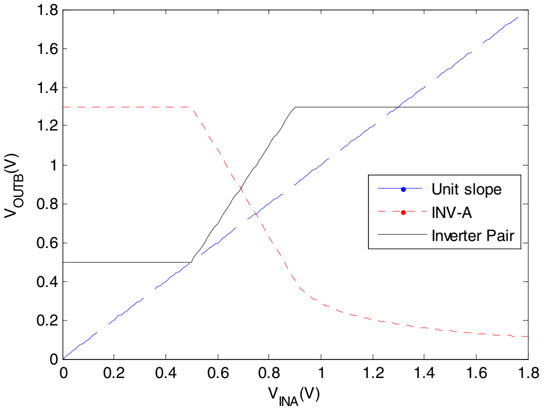

Figure 3 Transfer characteristics of inverse Widlar generator

$$V_{OUTA}=\begin{cases} V_{DD}+V_{Tp} & ,V_{INA}<V_{Tn} \\ V_{DD}+V_{Tp}-\sqrt{\dfrac{1}{\theta_1}}\left(V_{INA}-V_{Tn}\right) & ,V_{Tn}<V_{INA}<V_{Tn}+\left(V_{DD}+V_{Tp}\right)\left(\dfrac{\sqrt{\theta_1}}{1+\sqrt{\theta_1}}\right) \end{cases} \tag{1}$$

where $\theta_1=\dfrac{\mu_p W_5 L_1}{\mu_n W_1 L_5}$.

The upper equation is valid when M_1 cutoff and M_5 is saturated and the lower equation is valid when both transistors are saturated. Correspondingly, the second inverter is characterized by

$$V_{OUTB}=\begin{cases} V_{Tn} & ,V_{DD}+V_{Tp}<V_{INB} \\ V_{Tn}+\left(\dfrac{\sqrt{\theta_2}+\sqrt{\theta_3}}{2-\sqrt{\theta_4}}\right)\left(V_{DD}-V_{INB}+V_{Tp}\right) & ,\dfrac{V_{Tn}+\left(\dfrac{\sqrt{\theta_2}+\sqrt{\theta_3}}{2-\sqrt{\theta_4}}\right)\left(V_{DD}+V_{Tp}\right)}{1+\left(\dfrac{\sqrt{\theta_2}+\sqrt{\theta_3}}{2-\sqrt{\theta_4}}\right)}<V_{INB}<V_{DD}+V_{Tp} \end{cases} \tag{2}$$

where $\theta_2=\dfrac{\mu_p W_4 L_2}{\mu_n W_2 L_4}$, $\theta_3=\dfrac{\mu_p W_4 L_3}{\mu_n W_3 L_4}$, $\theta_4=\dfrac{W_2 L_3}{W_3 L_2}$. For the second inverter, the upper equation is valid when M_4 is cutoff and both M_2 and M_3 are saturated. The lower equation is applicable when all three transistors are in saturation. Assume θ_1,θ_2 and θ_3 are all equal to 0.5 and θ_4 is 1, the characteristic of the inverse Widlar bias generator is shown in the Figure 3. The dashed line is the unit slope line, the dotted line is the transfer curve of the inverter A, and the black line is the inverter pair transfer characteristic.

Then, the general inverter pair transfer characteristics are plotted in Figure 4. The dashed straight line has the unit gain when the V_{INA} equals to V_{OUTB}, and the operating points must lie on the unit gain line since V_{INA} and V_{OUTB} are connected. The inverter pair loop gain is always positive, and for different sizing of the circuit, the loop gain can be lesser, equal, or greater than one at the crossing point. The loop gain of two inverters at the stable equilibrium operation points is always less than one.

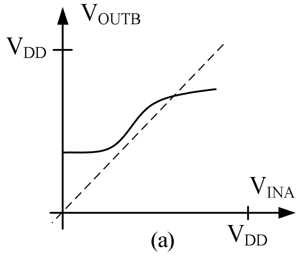

Figure 4 Broken inverter loop transfer characteristic

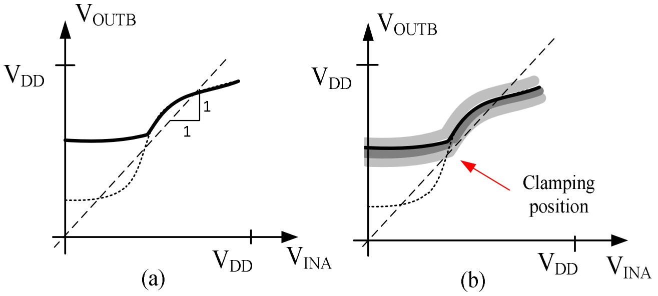

Figure 5 (a) Start-up circuit is included (b) Process variation

Based on the analytical plots, the transfer characteristic can be classified in two categories as following:

1) *Case1:One crossing point*

As shown in the Figure 4(a), there is only one single and stable crossing point, so apparently no start-up is needed. But, if the lower concave curve is very close to the unit gain line and the curve will move back and forth due to the variation of the process parameter. Then, transfer curve will cross with the unit gain slope. The detail explanation and simulation will be provided due to process variation in the later paragraphs.

2) *Case2:Three crossing point*

Figure 4(b) suggests that there are three crossing points exist in the system. The slop of the middle one is greater than one, so the point is metastable. But, there are still two stable operating points left which cause the start-up problem. In this case, start-up circuit needs to be carefully designed to ensure the reference generator operate in the correct stable point.

B. Start-up Circuit.

The issue for the start-up now can be seen by the transfer characteristic shown above. The multiple crossing points when the loop-gain is less than one in the transfer curves are causing problem. The simulator may find the stable equilibrium state that the circuit supposed to operate at fortunately, but without appropriate start-up design, the circuit may fail anytime unexpected due to the existence of another stable point. Therefore, it is important to add start-up circuit to force the circuit operating at one desired crossing point.

The start-up circuit plays a role to reduce the number of crossing point to one by modifying the transfer characteristic curve. As shown in the Figure 5(a), the dotted line is the original curve without the start-up circuit, and a start-up circuit acts as a clamp to limit the voltage to avoid the unwanted stable points. In this example, the goal is to express the upper stable point in the reference generator.

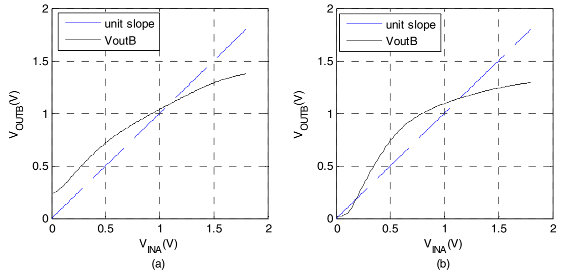

Figure 6 Simulated transfer characteristic of the bias generator

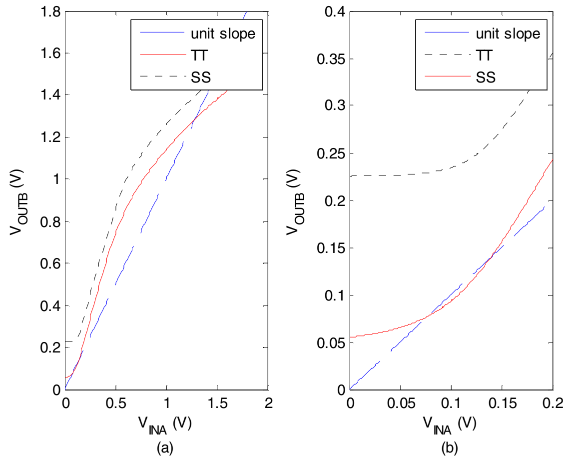

Figure 7 Process variations of the vulnerable transfer characteristic

Although there is only one stable operating point in the inverter pair loop transfer curve after adding the start-up circuit, the variations of the process variation and temperature over operating range need to be taken into account. Figure 5(b) shows the variation around the nominal value. The hazard condition would happen if the clamping position as the arrow shown on the plot is still too close to the unit slope line, and the circuit may find the undesired stable point. Also, the one crossing point case mentioned earlier without start-up circuit has similar characteristic to the modified generator. So, it is critical that a good start-up circuit design be robust to variations in the design and model parameters.

Adding a start-up circuit not only limits the stable operating point, it also helps the reference generator start-up faster when initially turn on the supply. So, it is still an attractive benefit to build the start-up circuit in the cases where a start-up circuit may not be necessary.

IV. SIMULATION RESULTS

The inverse Widlar biasing generator has been designed for demonstrating the new efficient method and simulated in 1P6M 0.18um process using BSIM3v3 model by Cadence.

A. General Transfer Characteristic of Case1 and 2

The simulation results shown in Figure 6 demonstrate that different inverter pair loop transfer characteristics exist with various sizing, and the slopes around the desired stable crossing points are less than one. Figure 6(a) and 6(b) show the simulation results of one and three operating points

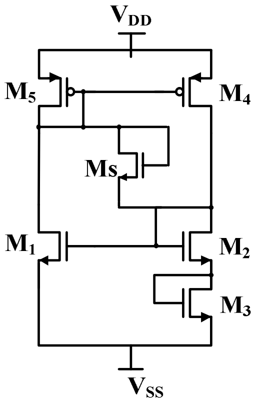

Figure 8 Reference generator with start-up device

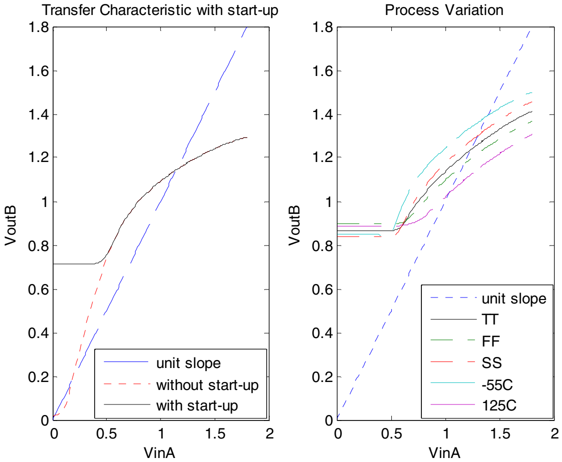

Figure 9 The simulated transfer characteristic with start-up and the process variation

respectively. The circuit in Figure 6(a) has only one crossing point and do not need any start-up. Figure 6(b) shows the case where a start- up circuit is required.

Figure 7 shows the hazard situation when there is only one stable crossing point in the typical case, but it is vulnerable due to the process variation which can be shown in a close look in Figure 7(b). Both Typical and NMOS slow-PMOS slow which is the worst case are simulated, and around lower voltage range, the extra stable point is shown in the NMOS slow-PMOS slow corner. The circuit is no longer stable due to process variation and a start-up circuit must be included. A set of simulations should be done when considering all the design parameter and process variations.

B. Start-up Circuit

By adding a simple and sized adequately diode-connected device to the reference circuit as shown in the Figure 8 [8], in Figure 9(a) shows the simulation results that the transfer characteristic of the two inverter loop has been changed from red dotted line to black solid line, and the transfer curve keeps the desired stable operating point.

A further simulation has been done to show that this designed example is robust to the process variation, and also suitable if the bias generator circuit works within a temperature range from -55˚C to 125˚C. Figure 9(b) shows there always exists one operating point over all the corners and temperature range.

V. CONCLUSION

The start-up issue is important generally for the DC-DC converter, bias generator, voltage/current references and the bias generator based temperature sensor. Although many paper bring up this issue, but most of them were focusing on designing a better start-up circuit based on transient simulation. And, the challenging on simulating the start-up issue has also been discussed in the section II. Providing an efficient way to help designing a better start-up circuit, the inverter pair loop transfer characteristics is a neat and reliable solution. This new method provides a practical way to circumvent the start-up simulation problem. It can also help to check if a circuit really needs a start-up circuit; for example, the new multiple-V_T based temperature sensor [3] does not need any start-up circuit base on the transfer characteristic analysis. This method can be also used to check any loops with the potential of more than one stable crossing point; thus can give a though for circuit designers to solve the start-up circuit problems.

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