Practical Methods for Verifying Removal of Trojan Stable Operating Points

Yen-Ting Wang, Degang Chen, Randall L. Geiger

Dept. of Electrical and Computer Engineering
Iowa State University
Ames, IA, 50010
yentingw@iastate.edu, djchen@iastate.edu. rlgeiger@iastate.edu

***Abstract* — Several methods that can be used to verify effectiveness of startup circuits in eliminating known stable Trojan operating states will be discussed. It will be shown that some widely used approaches do not guarantee Trojan states have been removed. Some of the methods introduced appear to be more practical to work with than others. These methods can also be used to identify the presence of unknown stable Trojan states in many useful circuits.**

Keywords: Multiple operating points, Trojan state elimination , Start-up Circuit, equilibrium points, references generators, self-bias generators

I. Introduction

It is well known that many useful circuits are plagued by the presence of undesired equilibrium (operating) points and that these Trojan equilibrium points must be eliminated with Trojan State Elimination (TSE) circuits for proper circuit operation. Self-stabilized bias generators, voltage and current references, log-domain filters, and bootstrapped feedback networks are well-known applications where stable Trojan operating points often occur [1,2,3]. But there are many other applications where Trojan operating points can appear as well. Although the presence of Trojan operating points are often known early in the design process, on occasion designers are not aware of the presence of Trojan operating points until after circuits have been fabricated. The task of identifying the presence of Trojan operating states and verifying removal with start-up circuits is complicated by the fact that existing circuit simulators provide a single solution (or operating point), not multiple operating points nor all operating points when more than one operating point is present.

TSE techniques have been studied and developed for different applications and the corresponding circuits are often termed "start-up" circuits though the latter term can be misleading since it is often associated with a temporal process of controlling when biasing voltages actually appear in different parts of a system when power is supplied to a circuit. Using a "start-up" circuit to control when power is applied to a circuit may circumvent having the circuit enters a known or unknown stable Trojan state most of the time but if the stable Trojan state exists, unanticipated transients can cause the circuit to enter the Trojan state and thereby cause the circuit to fail. The need for a TSE circuit is often not apparent and often recognized only by the experience of a circuit designer.

This work has been sponsored, in part, by the Semiconductor Research Corporation and by the National Science Foundation.

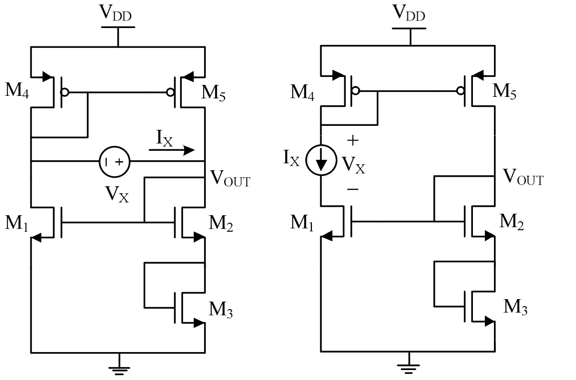
Several methods have been developed for finding operating points [4,5]. Some algorithms based upon piecewise-linear approximations of all nonlinear devices provide all operating points of a circuit [6,7] but implementation of these algorithms for even simple circuits is tedious and computation time is prohibitive if the circuit is very large. Homotopy methods are widely used to trace DC solutions though these methods do not guarantee all operating points will be identified and computation time can be large as well. Some papers also discuss how to determine whether an operating point is stable or unstable after the operating point has been identified [8,9]. However, simple and efficient methods that are guaranteed to find all operating points in either SPICE or SPECTRE in even rather simple circuits do not exist.

In this work, simple methods for verifying the effectiveness of TSE circuits for removal of known Trojan states will be discussed. Though the methods are applicable to a large number of well-known circuits that are vulnerable to the existence of Trojan states, emphasis here will be restricted to applying these methods to the well-known inverse-Widlar bias generator. These methods can also be used to identify all Trojan states in many useful circuits though no attempt will be made in this work to develop conditions under which all Trojan states will be identified.

Traditional transient simulation methods that are often used to assess performance of start-up circuits are discussed briefly in Section II. In Section III, intact-loop and broken-loop continuation methods for identifying multiple operating points are discussed. Section IV gives design and simulation examples to compare those approaches. A summary of this work is presented in Section V.

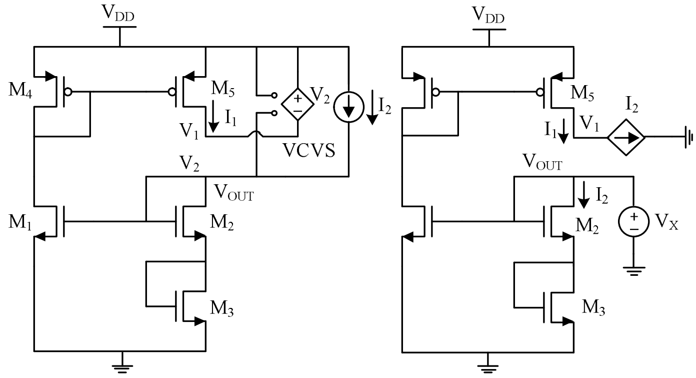
II. Transient Simulation Methods for TSE Verification

A standard practice in industry for verifying that a TSE circuit is effective is to run repeated transient simulations, often with a linear ramp up of the supply voltage, to verify that the circuit "starts up" correctly. With this approach, it can be concluded that if all energy storage elements in the real circuit have the same initial conditions as were used in the simulation and if the supply voltage ramp agrees with the simulation ramp, then the circuit will reach the observed operating point after an acceptable delay from the time the transient analysis starts. Although this approach often results in TSE circuits that serve the intended purpose, it does not guarantee that all serve



(a) (b)

Figure 1 Intact continuation method (a) voltage node sweeping type
(b) current branch sweeping type



(a) (b)

Figure 2 Break-loop continuation method
(a) current branch sweeping type (b) voltage node sweeping type

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.

III. Continuation Methods for TSE Verification

Circuit-level continuation methods for TSE verification often involve the introduction of a voltage or current source that can be swept to trace operating points of a circuit. This can be viewed as a Homotopy approach implemented at the circuit level. When certain conditions are satisfied, this method can be used to identify valid operating points of a circuit. The most common approach in this class involves insertion of sources that do not break any loops in the circuit thereby circumventing concerns about loop loading when a feedback loop is broken. Methods in which feedback loops are broken can also be used provided the operating points are not disturbed by breaking the loops.

A. Intact-Loop Continuation Methods

Green [10] proposed an intact-loop continuation method to verify the effectiveness of a startup circuit in removing a known Trojan operating point. With the Green method, a voltage source is inserted between two nodes in the circuit and the voltage is swept over a predetermined range and the current flowing through the voltage source is monitored. All points on the resultant voltage-current transfer curve are operating points of the circuit and these operating points could be stable or unstable points. This method is simple and computationally efficient and for many useful circuits will identify all operating points. Fig. 1(a) shows application of the Green method to the inverse-Widlar bias generator.

A counterpart intact-loop continuation method involves inserting a current source in a branch of the circuit as shown in Fig. 1(b). With this method, sweeping the current will provide operating points of the original circuit at all points where the voltage across the current source equals zero. This method is also simple and computationally efficient and for many useful circuits will identify all operating points. However, with the latter method, determination of the range over which the current should be swept may require some effort.

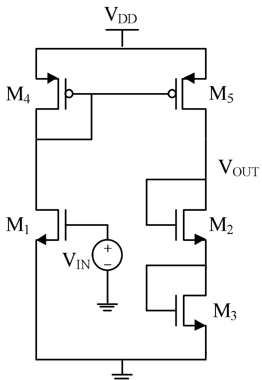


Figure 3 A special case for break-loop voltage node sweeping

Both methods suffer from the requirement of very accurately simulating very low currents since two of the operating points of this circuit are obtained when the circuit is operating in weak inversion. With the current-sweeping of Fig. 1(b), the sweeping current should always be positive making a logarithmic sweep practical for identifying low-current operating points. The use of a logarithmic current scale is not viable for identifying where currents vanish with the Green method.

B. Break-loop Continuation Method

Fig 2(a) shows a continuation method that involves breaking the feedback loop [11] and driving the loop with a current source at the break[11]. With this approach, a voltage control voltage source (VCVS) is incorporated to assure that loop loading is not altered at operating points of the circuit and a sweep is made of the current I_1. Any nodal voltage that is generated from the sweep when I_1=I_2 is an operating point. By using a logarithmic current sweep, the operating points of the

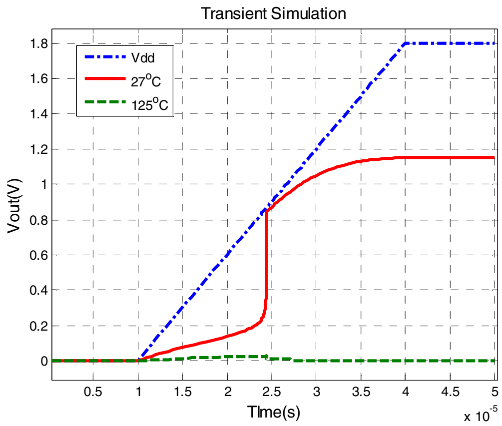
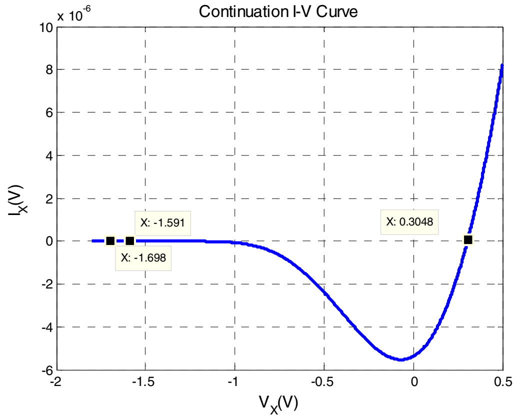
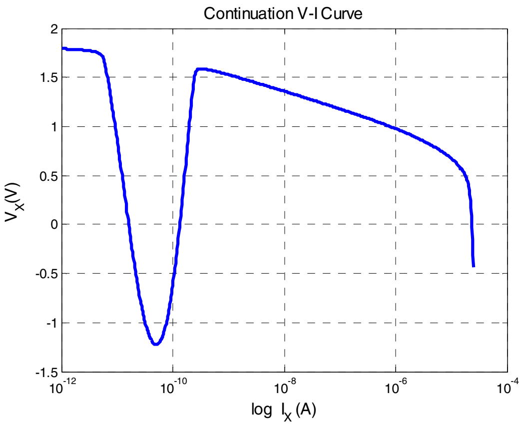


Figure 4 Transient Simulation



(a)



(b)

Figure 5 Simulation results for intact-loop continuation method (a) Green voltage node sweeping (b) current branch sweeping type

circuit can be identified even when the devices operate in weak inversion. Fig 2(b) shows a continuation method that involves breaking the feedback loop and driving the loop with a voltage source at the break[11]. With this approach, a current controlled current source (CCCS) is incorporated to assure that loop loading is not altered at operating points of the circuit and a sweep is made of the voltage V_X over a predetermined range. Any nodal voltage that is generated from the sweep when V_1=V_X is an operating point. From a practical viewpoint, the sweep range can be readily determined and the need for logarithmic sweeping is eliminated.

A third break-loop continuation method is shown in Fig. 3 whereby the loop is broken at the gate of a MOSFET [12] and the loop is driven by a voltage source inserted at the break, V_{IN}. Since the break is made at the gate of a MOS device where the input impedance is ideally infinite, loop loading is not affected by this break. This is applicable for MOS circuits because the input impedance at the break is ideally infinite. With a readily determined predetermined sweep range, any voltage where V_{OUT}=V_{IN} is an operating point. This could be viewed as a special case of the approach of Fig. 2(b) where the CCCS is not needed since the controlling current is zero.

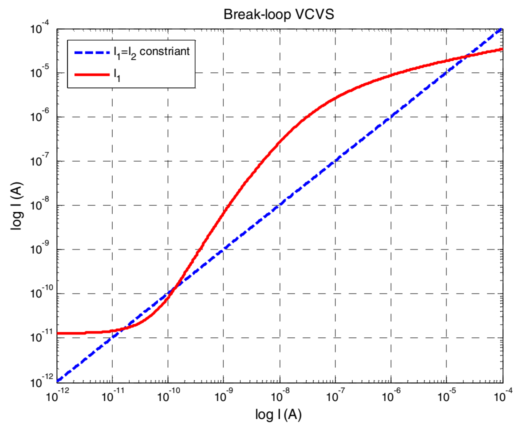
IV. EXAMPLE DEMONSTRATION AND SIMULATION RESULTS

The inverse-Widlar circuit has been designed for demonstrating the six methods discussed in the previous sections for finding multiple operating points. The circuit has been designed to have three operating points when operating without a TSE circuit. All simulations were made using the Typical/Typical 1P6M 0.18um BSIM3v3 models in the Spectre simulator running under a Cadence environment.

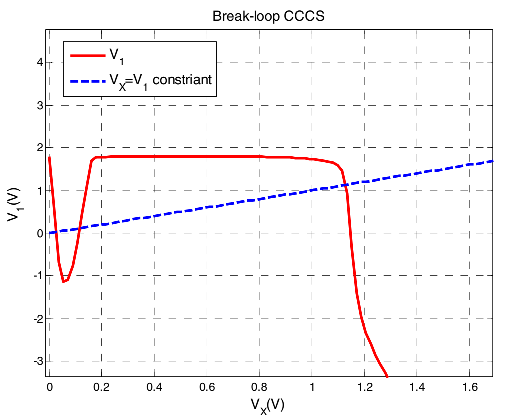
The traditional transient simulation method of slowly ramping the supply voltage V_{DD}, as shown in Fig. 4, settles to the desired operating point at 27˚C even without a TSE circuit showing the ineffectiveness of using this method for verifying that Trojan operating. Doing the same simulation at a higher temperature at 125 ˚C does cause this circuit to get stuck at the stable Trojan operating point though there is no guarantee that the Trojan operating point will be found by varying temperatures with this approach.

As expected, simulation results show that all five continuation methods successfully identified all operating points in this circuit. Fig. 5 shows the intact-loop continuation methods using voltage source and current source respectively sweeping respectively. In Fig. 5(a), with a sweep of the voltage in the circuit of Fig. 1(a), the right zero crossing point can be observed easily but the other two operating points are not easy to verify in the plot since they occur at very low current levels. When applying a linear current source sweep of the branch current in the circuit of Fig. 1(b), two of the operating points will be missed unless the step size is extremely small since these two operating points occur at very low current levels. However, with using logarithmic-spaced points, all three operating points are readily identified as shown in Fig. 5(b). Logarithmic current sweeping is practical in this case since the current will always flow from V_{DD} to V_{SS} in the left part of the circuit.

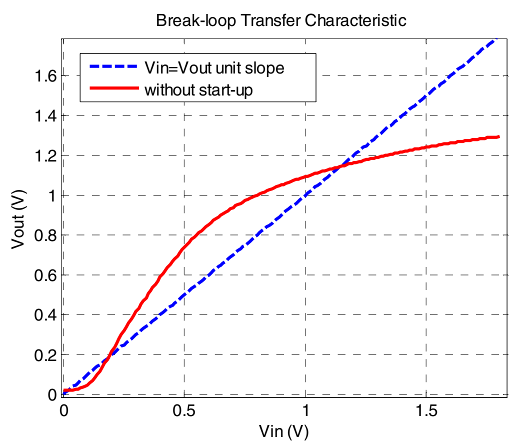
Fig. 6 shows the simulation results for three different break-loop continuation methods. The current-current plot of Fig. 6(a) is based upon the current sweep of Fig. 2(a). Although only two distinct stable operating points can be identified from the simulation results presented [11] where linear axis were used, all three operating points are distinctly present using a logarithmic sweep axis. In Fig. 6(b), the voltage sweep for the break-loop method of Fig. 2(b) was used. All three operating points are readily identified from this plot. Fig. 6(c) shows the voltage-voltage transfer characteristics from the break-loop gate voltage sweep of Fig. 3. The three operating points



(a)



(b)



(c)

Figure 6 Simulation results for break-loop continuation method (a) current branch sweeping type (b) voltage node sweeping type (c) Special case

corresponding to the intersection with the $V_{OUT}=V_{IN}$ line are readily apparent from this plot.

Though all five continuation methods successfully identified all operating points for this circuit, it was easier to identify the Trojan operating states with the current sweep of Fig. 1(b) and the voltage sweep of Fig. 2(b). When these methods are used to verify the effectiveness of a TSE circuit, simulations should be run over all process corners and over all temperatures to guarantee that the Trojan operating points have been eliminated.

V. Conclusion

The traditional supply ramp method is ineffective at verifying effectiveness of a start-up circuit as was demonstrated by a simple example. Five different methods for verifying the effectiveness of a start-up circuit at removing Trojan operating points were discussed. Although all successfully identified all operating states in the sample circuit considered here, this comparison suggests that some may be more practical than others for at least certain classes of circuits. Although the five continuation-method based approaches are effective at verifying removal of Trojan operating states, they will successfully identify all operating states in some of the more widely used circuits that may need start-up circuits for proper operation.

References

[1] G.C.M. Meijer and J.B. Verhoeff, , "An Integrated Bandgap-Reference," *Solid State Circuits Conf. (ESSCIRC), 1975 First European* , pp.40-41, 2-5, Sept. 1975

[2] C. Zhao, J. He, S.-H. Lee, K. Peterson, R. L. Geiger and D. Chen , "Linear Vt-based temperature sensors with low process sensitivity and improved power supply headroom," in *Proc. IEEE Int. Symp. Circuits Systems,* pp.2553-2556, May 2011

[3] R.M. Fox and M. Nagarajan, "Multiple operating points in a CMOS log-domain filter," in *Proc. IEEE Int. Symp. Circuits Systems,* vol.3, pp.689-692, Jul 1999

[4] L.B. Goldgeisser and M.M. Green,"A novel algorithm that finds multiple operating points of nonlinear circuits automatically," in *Proc. IEEE Int. Symp. Circuits Systems* vol.3, pp.558-561, Jun 1998

[5] R.C. Melville, L. Trajkovic, S.-C. Fang and L.T. Watson, "Artificial parameter homotopy methods for the DC operating point problem," *IEEE Trans. Computer-Aided Design*, vol.12, no.6, pp.861-877, Jun 1993

[6] L. O. Chua and R. L. P. Ying, "Finding all solutions of piecewise-linear circuits", *Int. J. Circuit Theory Appicat.*, vol. 10, pp.201 -229, 1982

[7] K. Yamamura and T. Ohshima, "Finding all solutions of piecewise-linear resistive circuits using linear programming," *IEEE Trans. Circuits Syst.-I,* vol.45, no.4, pp.434-445, Apr 1998

[8] M.M. Green and A.N.Jr. Willson, "How to identify unstable DC operating points," *IEEE Trans. Circuits Syst.-I,* vol.39, no.10, pp.820-832, Oct 1992

[9] M. Tadeusiewicz, "A method for identification of asymptotically stable equilibrium points of a certain class of dynamic circuits," *IEEE Trans. Circuits Syst.-I,* vol.46, no.9, pp.1101-1109, Sep 1999

[10] H. Wen and M. M. Green, "Use of a continuation method for analyzing startup circuits," in *Proc. IEEE Int. Symp. Circuits Systems*, pp.1527-1530, May 2010

[11] L. Han, Y. Wang, X. Zhang, Y.Dai and Y. Lu, "A simple and effective method to achieve the successful start-up of a current reference," *J.of Semiconductors*, vol.2, no.8, 2012

[12] Y.-T. Wang, C. Zhao, R. L. Geiger, D. Chen and S.-C Huang, "Performance verification of start-up circuits in reference generators," *IEEE Int. Midwest Symp. Circuits Systems,* pp.518-521, Aug. 2012