Effectiveness of Circuit-level Continuation Methods for Trojan State Elimination Verification

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Abstract — **A circuit is vulnerable if Trojan state appears, verification processes are needed to ensure the circuit is robust over temperature and process variation. Circuit-level continuation methods finding all DC operating points are summarized in this work. The discussion of where to apply continuation methods in the circuit and the minimum requirement of simulation steps in a circuit will be shown.**

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

I. INTRODUCTION

Many useful circuits that have Trojan (undesired) DC operating point play a key role in the analog circuitry. Circuit designers are aware of the need of Trojan State Elimination(TSE) circuit which is also called start-up circuit. Although people develop viable different TSE techniques, there are few practical methods to verify the effectiveness of TSE circuit.

Transient simulation is usually run to verify if the circuit starts up correctly, that is, to give certain time delay of supply voltage and check if the circuit operating points move to the desired operating point. Though this method has been widely use in circuit community, it does not show that a start-up circuit removes the undesired stable point, and it cannot guarantee the circuit always operate correctly after fabrication. Any unexpected interference may easily change the operating state.

Homotopy algorithm has been developed for finding operating points [1,2,3]. They are widely used in SPICE simulator to trace DC solutions and find the convergence. However, the simulator will only provide one DC solution, so additional program is needed to find operating points. Also, these methods do not guarantee all operating points will be identified and computation time is prohibitive if the circuit is very large. Contraction method [4] is also developed to find all operating points, yet it can only apply on bipolar devices which is not useful with modern CMOS process.

Recently, circuit level continuation methods have been developed [5,6]. Some appear more attractive property than others. Geiger [7] shows both intact-loop and break-loop continuation methods can find all operating points in a single positive feedback loop circuit.

From the results in [7], one can conclude that the crossing points are easier to be seen when the return parameter is voltage in both intact and break loop methods. It is obvious because of the characteristic of self-bias generator that the Trojan stable operating point happened when the transistors work in weak inversion cause nearly zero current.

There are two concerns when apply circuit level continuation methods to find the Trojan operating points. One is that nodes and loops are increasing as circuit becomes more complex; therefore, the choice of node and loop to apply continuation methods is significant. Different breaking node or branch would result different transfer curves, and one may contain better insight than another.

Another issue is the sweeping step number. Sweeping range and the resolution decide the step number. For voltage sweeping, the range is bounded by supply voltage which is decisive, instead, determination of the current sweeping range over which the current should be swept may require some effort. Accurately simulating of very low currents is required and thus result many step numbers. Step number is proportional to simulation time, and this trade-off should be considered.

We start the Trojan state verification process by firstly identify the positive feedback loop, and then apply the continuation methods to check the circuit. Finally, modify the circuit if the Trojan operating points exist and re-check the effectiveness of the TSE circuit. This paper focuses on the issue when using the circuit-level continuation methods, and two examples will be given to demonstrate the issues. Section II briefly introduces circuit-level continuation methods applying to find multiple operating points Section III discuss how the positive loop been defined and where to break the loop, and then a simulation of comparison between different breaking node is shown. Section IV shows the simulation time comparison between different circuit-level continuation methods. Section V concludes this work.

II. CIRCUIT-LEVEL CONTINUATION METHOD

Circuit-level continuation methods for finding all operating points often involve the introduction of a voltage or current source that can be swept to trace operating points of a circuit. When certain conditions are satisfied,

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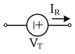
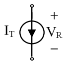
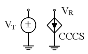
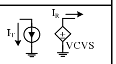
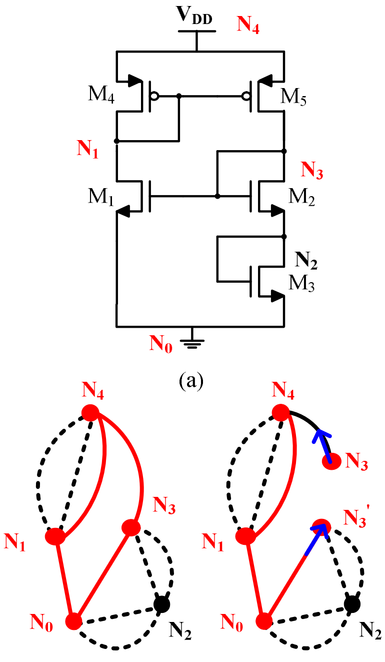
TABLE I. CIRCUIT-LEVEL CONTINUATION METHODS

	Continuation Method			
	Intact loop		***Break loop***	
	Current return	**Voltage return**	**Current return**	**Voltage return**
Test, x	V_T	I_T	I_T	V_T
Return, f(x)	I_R	V_R	I_R	V_R
Solution Condition	$I_R=0$	$V_R=0$	$I_R= I_T$	$V_R=V_T$
Symbol				



(a)

(b) (c)

Fig. 1 (a) Inverse-Widlar Circuit (b) Graph of Inverse-Widlar (c) Loop-breaking graph

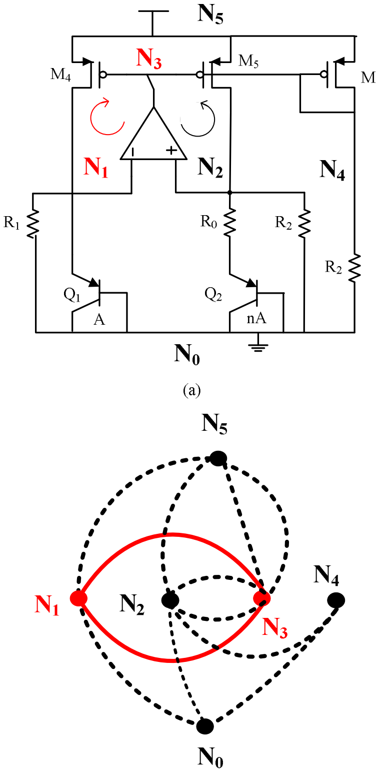
this method can be used to identify valid operating points of a circuit.

These circuit-level continuation methods can be view as giving a testing source to a circuit and a returning voltage or current satisfy the condition that identify the operating points. A summary of circuit-level continuation method is in Table I.

III. LOOP IDENTIFICATION

For simple circuit, loop can be identified by designer, but to automatically and systematically find all loops in larger scale circuit is still open since multiple loops will exist and the loops may couple to each other. These entire features increase the challenge to identify loops. Nevertheless, the well-known useful circuits with multiple operating points, such as bias generator, bandgap reference are with the same property that is they only contain single positive feedback loop. This property will lessen the challenge for finding the operating points.

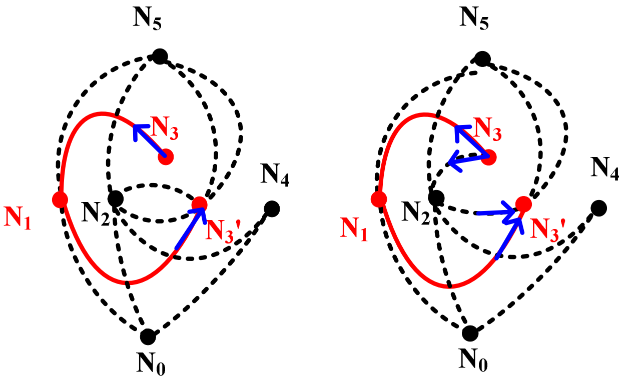
We now focus on single positive feedback loop circuits. First we convert the circuit to a graph. Based on well-developed graph theory, a graph contains node, edge, and loop can exist in a graph. Fig. 1 shows the inverse-Widlar example. Fig. 1(b) shows the graph of the Inverse-Widlar



(a)

(b)

Fig. 2 (a) Banba Bandgap reference (b) Graph of the circuit



(a) (b)

Fig. 3 (a) Positive feedback loop breaking (b) Positive and negative feedback loop breaking circuit which contains several loops, but only the loop that goes through N_1, N_4, N_3, N_0, and back to N_1 is the positive feedback loop. Other loops are with high negative gain. The edges represent the model of Transistors, and the nodes are the voltages nodes of the circuit. M_1 and M_5 are the common source stage with negative gain and provide the path between N_1 and N_3, thus compose a positive feedback loop. N_4 and N_0 are V_{DD} and V_{SS} respectively, so there is no need to check the operating point.

Next, the Homotopy method should be applied on the positive feedback loop. For intact-loop Homotopy methods, current branch sweeping type which also called voltage return type applies only to one branch, so either inserts the current source into N_1 or N_3 would work appropriately. Voltage node sweeping type which also called current return type needs two voltage nodes to insert the voltage source, so there is no other choice rather than N_1 and N_3. Same for the break-loop Homotopy method, either N_1 or N_3 can be break to find all operating points.

Another example is the Banba bandgap reference[8] in Fig. 2. Both transistor and op-amp can be converted to a graph, and the positive feedback loop is the loop which contains N_1 and N_3, and others are negative feedback loops. So, both N_1 and N_3 that on the positive feedback loop can be either insert a voltage source or break to apply Homotopy methods. Even though either N_1 or N_3 can be broke, different grouping way may show different characteristic curves. Fig. 3(a) shows the grouping way that remains the negative feedback loop intact, and since only the positive loop is broken, the Homotopy transfer curve is monotonic. Instead, Fig. 3(b) shows that both positive and negative feedback loop are broken, and the transfer curve will become non-monotonic because the negative feedback mechanism is no longer exist.

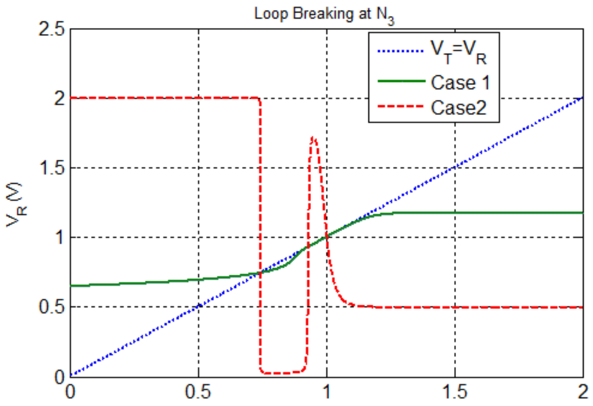


Fig.4 Simulation results comparing different grouping

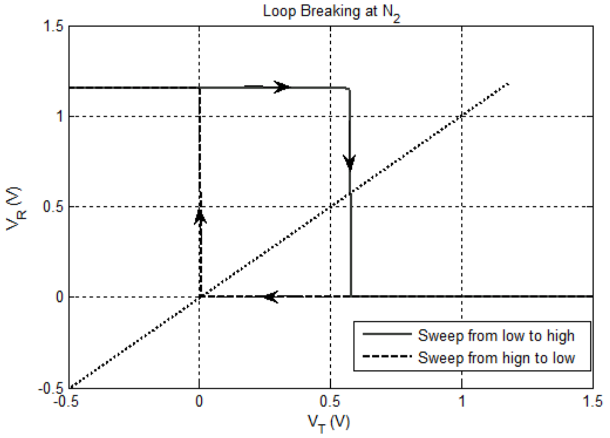


Fig.5 Hysteresis situation

Break-loop voltage return method has been used to demonstrate in Fig. 4 that the same DC operating points are found in different grouping approaches. Case 1 corresponding to break only the positive feedback loop which shows the monotonic characteristic, and in case 2, both positive and negative feedback loop are broken thereby the transfer characteristic curve is non-monotonic. In this example, case 2 shows a better image to identify the Trojan operating points.

Fig. 5 shows one situation that only breaks the negative feedback loop instead of the positive feedback loop. Since the positive feedback loop exists in the whole system, it produces hysteresis appearance. Continuation methods suffer from the hysteresis property. Under continuously sweeping, the actual transfer curve is not reflecting correctly, so the crossing points at the jumping transition are not the operating points. Therefore, with incorrect loop breaking, neither the desired operating points nor the Trojan stable operating points can be detected.

IV. SIMULATION STEPS

The circuit-level continuation methods may require different sweeping steps to detect the existence of Trojan stable operating points based on variant transfer characteristics they generate. Breaking or grouping differently also generates diverse curves thereby have different step requirements to find more than one operating point.

Simulation step numbers are decided by sweeping range and the step size. Voltage sweeping range is predetermined; instead, determination of the current sweeping range may require some effort. It is required to accurately simulate very low currents, but if the sweeping steps are enough to discover there is a trend to have Trojan operating point, it may not require numerous steps.

Simulation sweeping steps for finding the Trojan state operating points, which is to find more than one operating point, are shown in TABLE II and TABLE III for Inverse-Widlar bias generator and Banba bandgap reference respectively. Cadence tool is using to run parametric analysis, and all circuits are designed in AMI 0.6μm process. All simulations are choosing to break only the positive feedback loop and thus the transfer curve is monotonic. The symbol "X" means it cannot find more than one stable operating points, and "O" mean it can detect the circuit is vulnerable to Trojan state. The simulation results show that some circuit-level continuation method can find the Trojan operating points in fewer steps than other methods.

For the inverse-Widlar structure, although the crossing points are more visible in break-loop voltage return than intact loop current return method, the steps it needs are more than the other.

TABLE II. SIMULATION TIME FOR INVERSE-WIDLAR

Homotopy method / **Sweeping steps**	**Trojan State Detection Success(O)/Fail(X)**			
	Intact loop		***Break loop***	
	Current return	**Voltage return**	**Current return**	**Voltage return**
3	X	X	X	X
5	O	X	X	X
8	O	X	X	O
10	O	O	O	O

TABLE III. SIMULATION TIME FOR BANDGAP REFERENCE

Homotopy method / **Sweeping steps**	**Trojan State Detection Success(O)/Fail(X)**			
	Intact loop		***Break loop***	
	Current return	**Voltage return**	**Current return**	**Voltage return**
5	X	X	X	X
10	X	X	X	O
15	X	X	O	O
20	O	O	O	O

TABLE IV. COMPARISON BETWEEN MONOTONIC AND NONMONOTONIC

Transfer-Curve / **Sweeping steps**	**Trojan State Detection Success(O)/Fail(X)**	
	Non-monotonic	***Monotonic***
5	X	X
10	O	X
15	O	O
20	O	O

Table III shows that the break-loop voltage return method is prefer to use in Banba bandgap reference for verifying if Trojan operating points exist.

Table IV shows the difference of the need of sweeping step between monotonic case and non-monotonic case. The non-monotonic case shows its needs less steps to find the Trojan operating point and it is also obvious from Fig.4 that the slope of the crossing point in case 2 is much larger than in case 1.

V. CONCLUSION

The main target for using circuit-level continuation method is to verify the existence of Trojan operating points instead of finding all operating points. For the efficiency of the verification process, the minimum sweeping step number is found between different methods in Inverse-Widlar and Banba bandgap reference circuits. Some show it needs only half of steps to find the Trojan state.

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