New Technique for the Determination Through Commercial Software of the Stable-Operation Parameter Ranges in Nonlinear Microwave Circuits

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***Abstract*—In this paper, a new technique is presented for the global stability analysis of nonlinear microwave circuits using harmonic balance commercial software. The stable operation region in any two-parameter plane is determined from a combination of the bifurcation conditions and a new continuation technique. In the case of asynchronous instability, the quasi-periodic solution paths are entirely traced and their stability is analyzed, which allows the prediction of possible chaotic responses. The new method makes both kinds of analysis, limited so far to in-house simulators, accessible to any circuit designer. Here, it has been applied to a varactor-based frequency doubler with excellent agreement with the experimental results.**

***Index Terms*—Bifurcation analysis, continuation technique, frequency doubler, global stability, quasi-periodic route to chaos.**

I. Introduction

Nonlinear circuits of autonomous nature often exhibit phenomena like hysteresis, frequency division, or appearance of autonomous fundamentals, which are different types of bifurcations [1], [2]. Thus, the bifurcation prediction will be of a major interest in order to determine the circuit parameter ranges for stable operation. Such an analysis has been limited so far to in-house simulators. In order to make it accessible to any circuit designer, a new technique, based on the use of harmonic balance (HB) commercial software, is presented here.

The stability of nonlinear regimes is generally analyzed by considering a complex frequency perturbation over the steady-state solution, linearizing the system about this solution and applying the Nyquist criterion [1]. In this work, once the HB commercial software has provided the steady-state solution, this analysis is carried out by introducing into the circuit an auxiliary generator (AG) of negligible amplitude. Then its frequency is varied, calculating through HB the corresponding input immittance and checking out for the fulfillment of the oscillation start-up conditions.

As a parameter varies, the limit condition for stability provides the different bifurcations [1], [2]. These are identified here from the AG frequency value and its relationship with that of the steady regime. The stability borders on a two-parameter plane are obtained by combining each bifurcation condition with a new continuation algorithm, which makes use of the AG and is based on a parameter switch. The steady frequency divided or quasi-periodic responses are obtained by the nonlinear optimization of the auxiliary generator when a nonperturbation condition is imposed. The same switching-parameter algorithm is also used for tracing the solution paths, which may exhibit turning or infinite slope points.

The new technique is illustrated here by means of its application to a varactor-based frequency doubler, based on [3], exhibiting a quasi-periodic route to chaos. The tracing of the Hopf locus in the input power-input frequency plane has allowed the determination of the stable frequency-doubler operation zone. To our knowledge, this is the first time that a Hopf bifurcation locus from a periodic regime is obtained using commercial software. The steady quasi-periodic solutions and the quasi-periodic paths have also been obtained. Finally, the arise of a second autonomous fundamental has been detected, which provides a good estimation for the onset of chaos [2], [4]. Results have been successfully compared with those obtained from an existing in-house HB simulator and with measurements.

II. Analysis Method

A nonlinear steady-state solution of fundamental ω_{in}, obtained through commercial HB, will be considered. In order to analyze its stability, an auxiliary generator of value $\epsilon.\exp(j\omega_a t)$, with $\epsilon \cong 0$, is introduced into the circuit. This generator must have no influence for $\omega \neq \omega_a$, which may be easily ensured by means of an ideal filter. The conditions for the oscillation or subharmonic start-up are checked out by determining the input immittance Y or Z, observed from the auxiliary generator, and tracing the corresponding stability plot. As a parameter varies, bifurcations will be obtained when the plot crosses the origin in the clockwise sense. These will be of Hopf type for $\omega_a \neq m/n.\omega_{\text{in}}$ and of indirect type for $\omega_a = 1/2.\omega_{\text{in}}$. Thus, it will be possible to obtain the stability borders by imposing the conditions $Y = 0$, for a voltage perturbation, or $Z = 0$, for a current perturbation. In the former case, for tracing the Hopf locus, a sweep is carried out in the input frequency ω_{in}, obtaining for each ω_{in} value the E_{in} and ω_a values that fulfill $Y = 0$. This is done through a standard optimization in the commercial simulator. However, the bifurcation loci often exhibit turning points. To avoid the HB convergence problems near them, a parameter switch is

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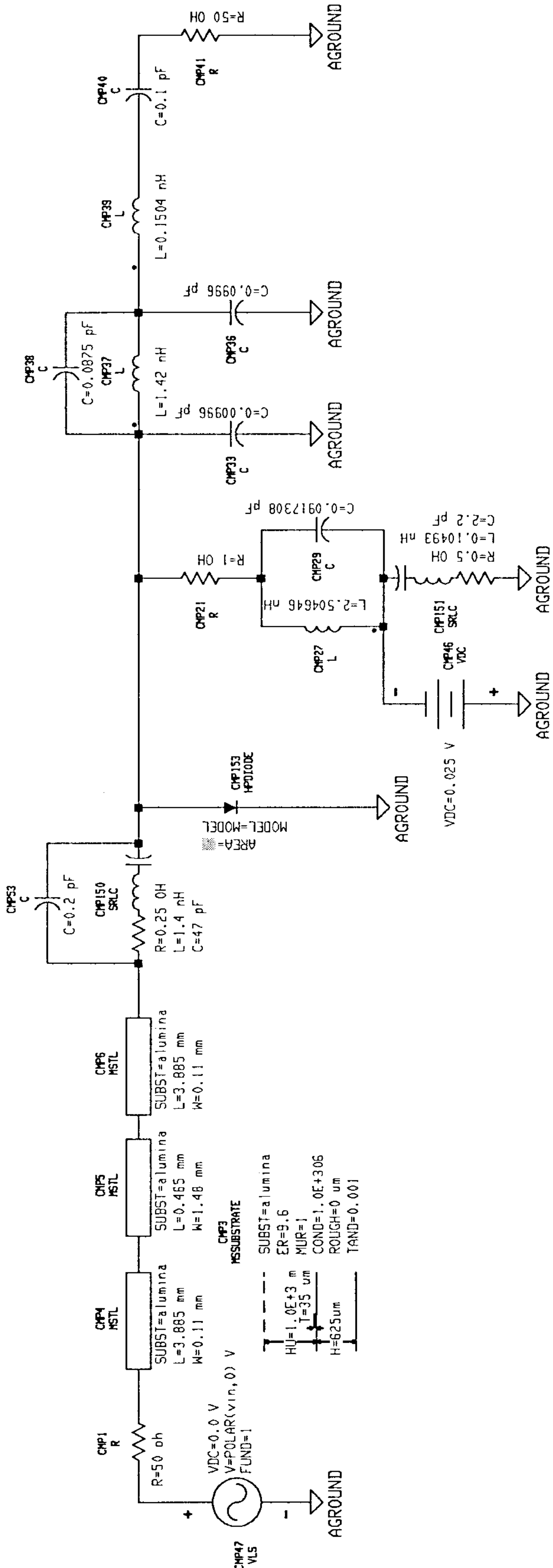
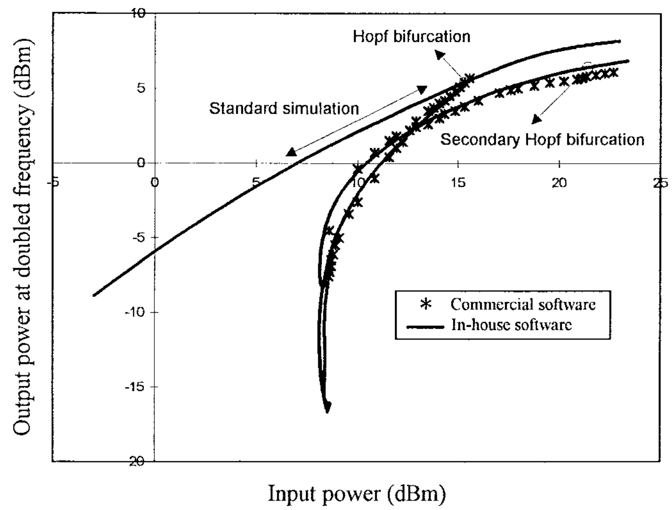
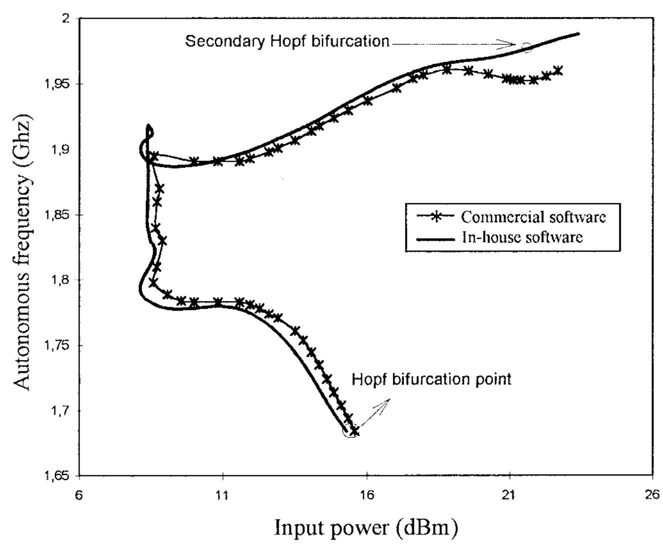


Fig. 1. Schematic of the frequency doubler.

carried out, proceeding to optimize ω_{in} and ω_a for each E_{in} value. This is equivalent to a rotation of the solution curve.



(a)



(b)

Fig. 2. Comparison between in-house and commercial software: (a) output power at the spectral component $2\omega_{\text{in}}$ for input frequency 3.7 GHz and (b) autonomous frequency variation.

For obtaining the steady quasi-periodic solutions, the AG amplitude A and frequency ω_a are optimized in the commercial simulator, in order to fulfill the nonperturbation condition $Y = 0$ or $Z = 0$. This analysis provides the nonperturbing generator value A^0, ω_a^0. When modifying a parameter μ, the generator amplitude A and frequency ω_a will be optimized for each μ value. However, near the turning points, of difficult convergence, A and μ must be optimized for each ω_a value, obtaining the entire quasi-periodic solution paths.

For the stability analysis of quasi-periodic solutions, the optimized auxiliary generator is kept at its nonperturbing value A^0, ω_a^0, which provides the commercial simulator with the steady-state operating point. A perturbation is then introduced, in the form of a second AG of negligible amplitude and frequency ω_{a2}. The stability is analyzed by sweeping ω_{a2} and observing the corresponding input immittance. To do this, only intermodulation products of coefficient ± 1 in ω_{a2} will be considered, which greatly reduces the complexity of the calculation.

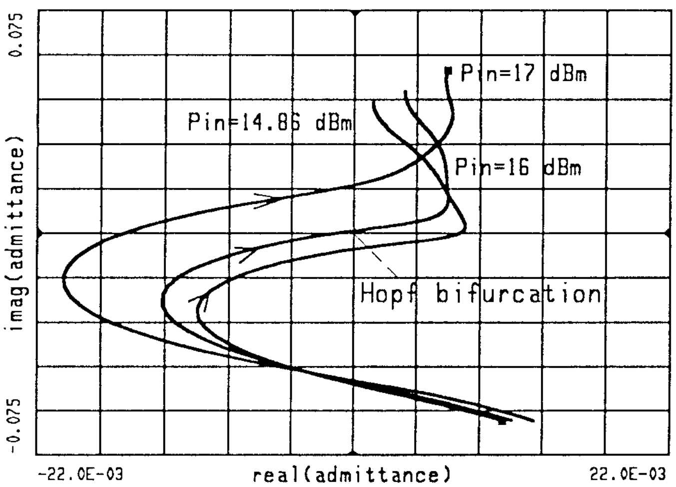


Fig. 3. Hopf bifurcation prediction for input frequency 3.7 GHz.

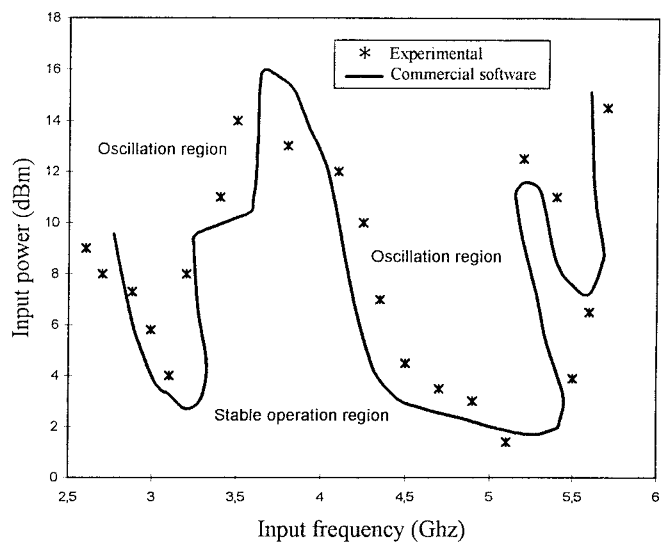


Fig. 4. Hopf bifurcation locus from the new commercial software method. Experimental points superimposed.

III. Application to a Doubler Circuit

As shown in [3], the dynamic negative resistance of varactor diodes for harmonic generation may be responsible for different kinds of instability and even chaotic behavior. In order to verify the proposed analysis techniques, a varactor-based frequency doubler 4–8 GHz (Fig. 1) has been designed here, following the topology of [3].

When increasing the input power at 3.7 GHz, the standard simulation in commercial HB only provides a periodic response, with no information about its stability or the possible coexistence of other solutions [Fig. 2(a)]. The new method has allowed the detection for $P_{\text{in}} = 15.9$ dBm of a Hopf-type bifurcation (Fig. 3), giving rise to a self-oscillation. Its effect on the spectral component $2\omega_{\text{in}}$ is the appearance of a new solution branch [Fig. 2(a)]. From the branching point, the standard simulation curve is unstable. When decreasing P_{in}, the associated hysteresis phenomenon makes the oscillation persist until P_{in} is reduced below 7 dBm. In Fig. 2(a), the quasi-periodic branch can be compared with the one resulting from an in-house simulator [2]. The minor discrepancies are due to a slight difference in the intermodulation products taken into account. The admittance polar plots predict an asynchronous instability of the quasi-periodic path from $P_{\text{in}} = 21.6$ dBm and a chaotic regime was actually observed. In Fig. 2(b), the variation of ω_a has been traced as a function of P_{in}.

In Fig. 4, the Hopf bifurcation locus has been traced in the plane $P_{\text{in}} - \omega_{\text{in}}$, with experimental points superimposed. It provides the border between the region of stable operation as frequency doubler and the oscillation region.

IV. Conclusions

In this letter a new technique, based on the use of commercial software, has been presented for the bifurcation analysis of periodic and quasi-periodic regimes of microwave circuits. The technique combines the well-known bifurcation conditions, with the use of a new continuation algorithm, taking also advantage of the commercial software optimization tools. The same continuation algorithm allows the tracing of the entire solution paths when a parameter is modified. The new technique has been applied for the determination of the stable operation conditions in a varactor-based frequency doubler. The quasi-periodic instability leading to chaotic behavior has also been detected. Excellent agreement has been obtained in the comparison with measurements.

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