SIMULATION OF MULTI-TONE IMD DISTORTION AND SPECTRAL REGROWTH USING SPECTRAL BALANCE

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ABSTRACT

Computer simulation of general microwave nonlinear circuits excited by a large number of input tones is addressed. The algorithm based on the spectral balance method, uses a new index vector technique which allowed the prediction of complex behavior such as spectral regrowth and noise power ratio performance of a class B power amplifier.

I. INTRODUCTION

Recent advances in telecommunications systems, particularly broadband services and mobile networks, continuously present new challenges to microwave computer aided design (CAD) tools. In one hand, to achieve higher output power and efficiency, amplifier circuits are being pushed to saturated classes of operation, and, on the other hand, circuit design linearity is permanently driven by improved system performance. Because of the complex nonlinear phenomena involved, microwave engineers no longer rely on the classic single carrier or two-tone tests. Alternatively, they are seeking new characterization procedures like the observation of the spectral regrowth produced in a nonlinear circuit excited by a modulated carrier, or even the identification of the newly generated spectral components when the circuit is expected to handle a very large number of input tones - the so-called noise power ratio test (NPR). Accompanying that scenario, an obvious need to incorporate prediction facilities of these experiments in today's microwave CAD simulation tools, appeared. However, the problem of simulating, in a digital computer, the response of a strong nonlinear circuit driven by a complex spectral signal is, until now, virtually unsolved.

In fact, neither time domain (SPICE like programs [1]), nor hybrid time domain/frequency domain (Harmonic Balance - HB - programs [2]) based packages, can be directly applied. Very recently, some hybrid alternatives based on the time domain integration of the envelope base band signal (Envelope Simulators - ES -) [3,4], were especially proposed to solve that kind of simulation problem, but they still have problems.

From this brief overview, one can conclude that nowadays, the best way to solve the problem of simulating nonlinear circuits driven by general multi-tone signals, is to select one of the available analysis methods that operate entirely in the frequency domain: Volterra series [5] or frequency domain harmonic balance - Spectral Balance (SB) [7].

Despite the many advantages presented by the Volterra series method, it is restricted to mild nonlinear regimes [6]. Thus, it is useless for predicting the nonlinear responses of any saturated circuit.

The spectral balance algorithm is specially appropriate for the present problem as it picks up the frequency representation of the excitation, and provides an output, in the same form. It performs all simulation steps without passing through time domain, thus obviating the need for any Fourier transform.

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In this paper we will apply the Spectral Balance Algorithm, with several improvements [9] to a multi carrier nonlinear amplifier. Using this amplifier we will present various simulation scenarios of spectral regrowth, NPR, and multi-tone IMD. Then, simulated and experimental results of nonlinear muti-tone excitation regime, obtained from that microwave class B amplifier, are compared.

II. SPECTRAL BALANCE ALGORITHM

As may be seen from the flow chart of Fig. 1, the spectral balance concept is similar to the well-known harmonic balance.

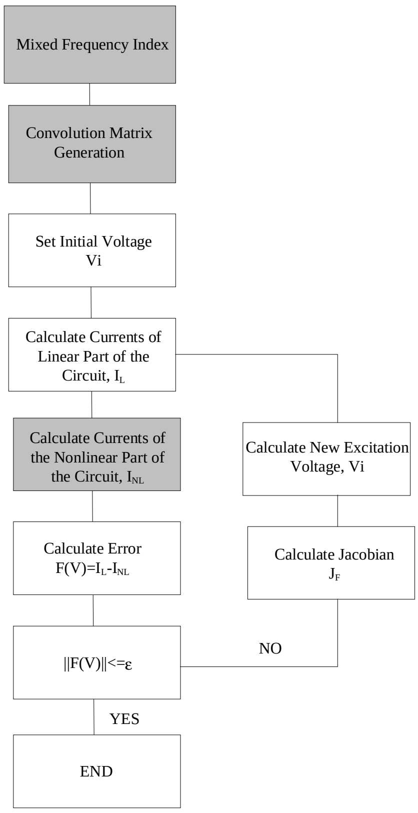

Fig. 1 - Simplified spectral balance flow chart.

The first shaded block plays a dominant role on the Spectral Balance application to large multi-tone excitations, as it defines the size of the system unknowns' vector, and, therefore, the computer memory and simulation time requirements. The way to generate the index vector for this type of excitation was already addressed by the authors in a previous publication [9]. The closed formula used is herein simply presented.

$$f_{central} = \begin{cases} \left(\dfrac{f_m + f_{m+1}}{2}\right) \cdot c, & \text{if number of tones is even} \\ f_m \cdot c, & \text{if number of tones is odd} \end{cases} \qquad (1)$$

with f_m and f_{m+1} the input central frequencies and **c** the nonlinear order; while the correspondent spectral widths located around the central frequency, $f_{central}$, may be calculated from:

Nº of newly generated tones = c.n-(c-1) (2)
with **n** the number of original tones.

For example, using this formula, and considering an input spectrum with 3 tones mixed to the 5^{th} nonlinear order, only 90 loops were sufficient to determine the whole index vector, against the 1331 loops that would be required by the previous combinatory techniques [7]. That difference has a fast increase as **n** grows.

The second shadowed block of Fig. 1 is the generation of the convolution matrix. It is needed to perform time domain multiplications and divisions in the frequency domain. This problem has already been studied by Steer [7] and a new way to generate it was proposed by the authors [9].

Since the SB algorithm operates entirely in the frequency domain, any nonlinear active device model should be described by some basis functions for which spectra calculations are not a too difficult task. One way to select those basis functions is to simply rely on the elementary arithmetic operations, since time domain soma addition and subtraction have a direct correspondent in the frequency domain, and multiplication and division can be mapped to spectral convolution and deconvolution. In this work, we adopted rational functions as the selected model's functional forms.

III. NONLINEAR MICROWAVE CIRCUITS ANALYSES

To prove the fitness of the proposed algorithm to the multi-tone IMD simulation problem, measured results of a two tone test and spectral regrowth

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observed on a class-B amplifier were compared to correspondent simulations obtained with an in-house developed SB simulator.

This power amplifier circuit was excited by 3 different types of signals: 1 - sinusoidal two tones; 2 - one carrier amplitude modulated by a pseudo random sequence and 3 - discretized flat continuous spectrum with a notch.

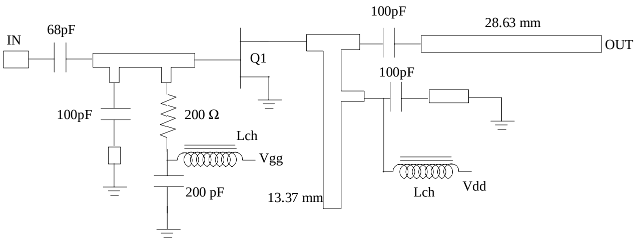

Fig. 2 - Schematic diagram of the implemented class B power amplifier prototype.

A.1. Two Tone Test

Results of two tone excitation obtained from a commercial HB package [8] and our SB simulator, were compared to the ones measured on the experimental prototype. The results are presented on Fig. 3 for one of the fundamentals, ω_2, and 2[nd] and 3[rd] order products at $\omega_1+\omega_2$ and $2\omega_2-\omega_1$.

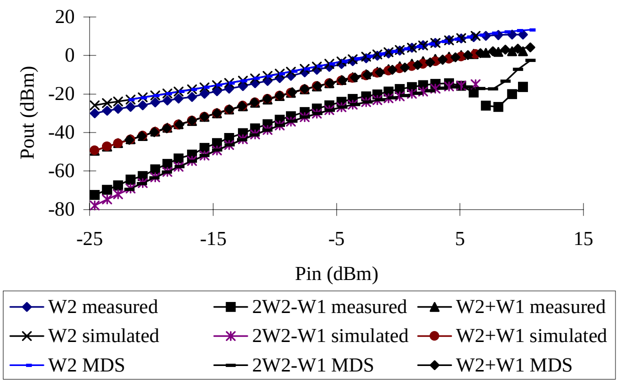

Fig. 3 - HB and SB two tone simulations and experimental results observed in the implemented class B amplifier.

These results can be considered in very good agreement. It should be noted that, although there are some small discrepancies between measured and simulated data, SB and HB results are exactly coincident, which possibly indicates active device modeling accuracy problems.

A.2. Spectral Regrowth Test

For this type of simulation, the excitation considered is presented on Fig. 4. There, the amplitude and phase of the individual excitation tones can be observed.

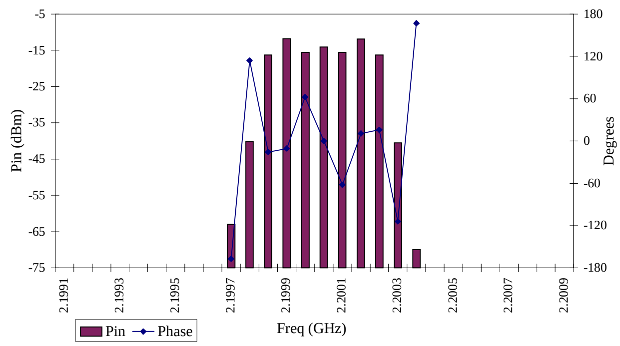

Fig. 4 - Input signal spectrum used for multi tone spectral regrowth tests.

Although calculations determined components' values until the 5[th] harmonic, only the output fundamental and its associated 3[rd] and 5[th] order spectral regrowth were plotted in Fig. 5.

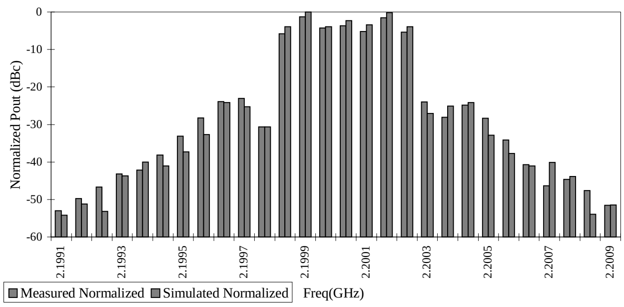

Fig. 5 - SB simulated and measured output spectrum obtained from modulated carrier spectral regrowth test.

By comparing these simulated and experimental results it can be easily concluded that our simulator gives a very good prediction of the real power amplifier behavior, when it is excited by a two or multi tone signals.

A.3. Broad band Noise Power Ratio Test

The excitation generally used to perform a NPR test is a continuous spectrum signal with random phase, since it is derived from a real noise generator. However, if this laboratory test is to be simulated in a digital computer, i. e., a finite state machine, some frequency sampling must be used [6]. The most obvious way to do that consists in using an uniform sampling rate, which enables the application of the above derived frequency index vector formulation.
Thus, in order to simulate a NPR test the circuit of Fig. 2 was excited by a signal consisting of a discretized spectrum with a notch, that spans from 2.1GHz to 2.3GHz. The phase of each of the 11 samples was considered random. 15 different random phase arrangements were simulated, and their results averaged. That average result is presented on Fig. 6.

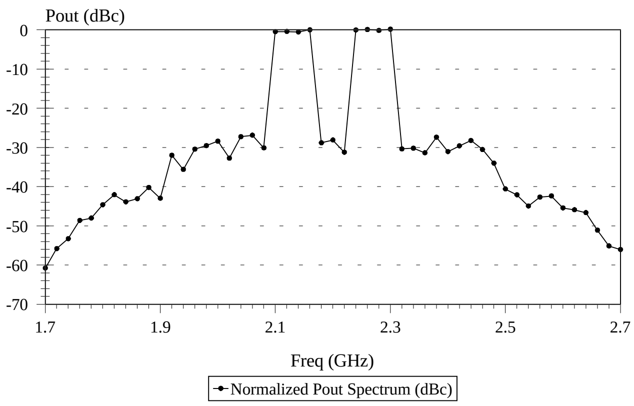

Fig. 6 - Output results of the simulated NPR test performed on the class B amplifier prototype.

As was expected, some distortion components appeared between the two input pseudo-noise bands. The ratio between the output fundamental signal level and these distortion components, about 28dBc, gives a measure of the NPR figure of merit for this power amplifier.

IV. CONCLUSIONS

In conclusion, this paper shows, for the first time, the simulation of general strong nonlinear phenomena observed in microwave circuits driven by complex spectra. It should be preferred to some previous published techniques for spectral regrowth [3,4,6] and NPR[3,4], since it is not limited to mild nonlinear regimes[6] nor to narrowband excitations [3,4].

ACKNOWLEDGEMENTS

This work was supported by JNICT with a doctoral grant, Praxis XXI/BD/5630/95 and the LIRA project, 2496/TIT/95, were this work was developed.

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