Intermodulation Distortion Analysis of FET Mixers under Multitone Excitation

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***Abstract.*- This paper presents an extension of the time-varying Volterra-series technique for evaluating intermodulation distortion (IMD) in FET mixers when excited by multitone signals. The mentioned nonlinear analysis tool is properly combined with an accurate device characterization in order to reproduce and control the FET distortion performance when it is employed for frequency conversion in small-signal regime. Good spectral regrowth and noise power ratio (NPR) predictions on a resistive mixer and on a class A amplifier confirm the validity of the proposed approach not only for time-varying but also for time-invariant applications.**

I. INTRODUCTION

The increased use of digital modulated and multicarrier signals in radiocommunication systems has imposed important changes in the way of characterizing the nonlinear distortion phenomena that may appear. In this sense, the classical two-tones intermodulation distortion test has evolved into more appropriate experiments: the adjacent channel power ratio (ACPR) and the noise power ratio (NPR) measurements.

Important efforts have been recently made in the field of nonlinear analysis tools for handling such complex signals. In amplifiers, techniques such as low-frequency transformation [1], transient envelope analysis [2], Volterra-series [3], or spectral balance [4] have evolved like robust solutions. However, very few results have been reported for other applications [5], and the mixer space is still quite empty.

In a mixer application, the RF excitation amplitude is usually much lower than the local oscillator (LO) injection. This condition has determined the feasibility of employing time-varying Volterra-series analysis (also known as large-signal/small-signal technique) for accurate IMD calculations [6] when one or two-tones are applied in the RF port [7], [8].

In this paper, we then propose a technique to extend this powerful nonlinear analysis method to the handling of more complex excitation signals, as most modern radio equipment demand. As an accurate IMD prediction also requires a proper device model, a recently developed equation based on the derivative characterization is employed [9].

II. MULTITONE TIME-VARYING VOLTERRA-SERIES ANALYSIS

Applying time-varying Volterra-series technique implies a two-steps solution: first analyzing the mixer behavior under the LO pumping signal (using harmonic balance, for instance), and second introducing the RF excitation as a small deviation from the LO time-varying previously calculated results [10].

In Fig. 1, we show the general topology of a single FET mixer for applying the second step of the previously mentioned technique. *Vg* could represent the RF signal in an active gate or drain mixer, a role played by *Vd* if the mixer were resistive. The linear elements have been represented through their conversion matrices. Igs^{NL}_i, Igd^{NL}_i, and Ids^{NL}_i are the i^{th} order nonlinear current sources associated to the respective main nonlinearities (*Cgs, Cgd and Ids*).

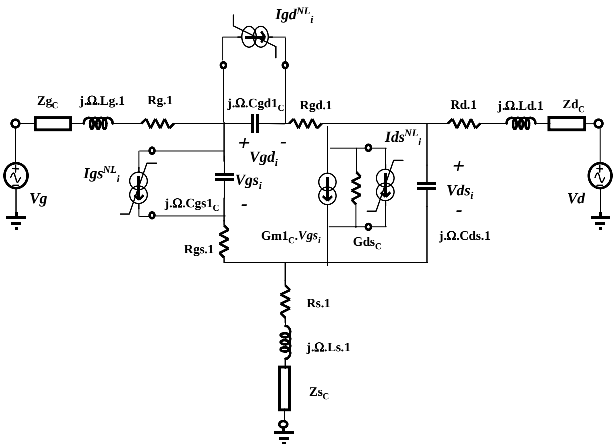


Fig.1 FET equivalent circuit for time-varying Volterra-series analysis.

The main challenge, when applying the nonlinear current technique with multitone signals, relays in the calculation of the nonlinear current sources (the rest of the steps are based on linear circuit calculations). To illustrate this situation, we will consider a simple case, the second order nonlinear current source for the predominant nonlinearity, *Ids(Vgs,Vds)*, whose Taylor-series expansion is represented as

$$
\begin{aligned}
&Ids(Vgs,Vds) = Ids(V_{GS},V_{DS}) + Gm1.vgs + Gds.vds + \\
&+ Gm2.vgs^2 + Gmd.vgs.vds + Gd2.vds^2 + Gm3.vgs^3 + \\
&+ Gm2d.vgs^2.vds + Gmd2.vgs.vds^2 + Gd3.vds^3 \qquad (1)
\end{aligned}
$$

The second order nonlinear current source could be calculated in time domain by

$$
\begin{aligned}
&ids_2^{NL}(t) = Gm2(t).vgs_1^{\,2}(t) + Gmd(t).vgs_1(t).vds_1(t) + \\
&+ Gd2(t).vds_1^{\,2}(t) \qquad (2)
\end{aligned}
$$

Or in frequency domain by,

$$
\begin{aligned}
&Ids_2^{NL}(\omega) = Gm2(\omega) * Vgs_1(\omega) * Vgs_1(\omega) + \\
&+ Gmd(\omega) * Vgs_1(\omega) * Vds_1(\omega) + \\
&+ Gd2(\omega) * Vds_1(\omega) * Vds_1(\omega) \qquad (3)
\end{aligned}
$$

A typical spectral distribution of a first order control voltage (Vgs_1 or Vds_1) is displayed in Fig.2. It is quite evident that a spectrum of this kind with the real frequency variable would be quite sparse and difficult to handle in a convolution product. However, the frequency domain nature of Volterra-series analysis lets us compress such sparse spectrum without affecting the convolution result. In spite of the minimum separation necessary between clusters or bands, to avoid aliasing when the convolutions are evaluated, the computational efforts can be greatly reduced.

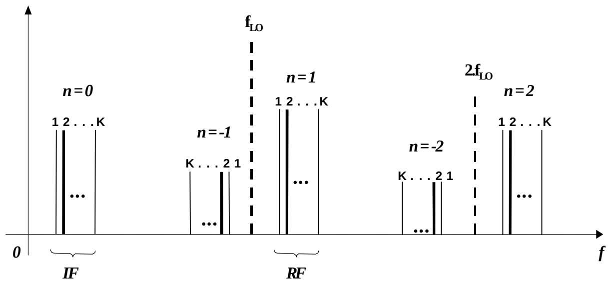


Fig.2 Spectrum of a first order control voltage. With a bold line we have represented the components of a typical first order voltage vector as employed in [10]. *K* represents the number of RF tones.

A critical point in each compressed spectrum convolution, $Vgs_1(\omega)*Vgs_1(\omega)$, $Vgs_1(\omega)*Vds_1(\omega)$ and $Vds_1(\omega)*Vds_1(\omega)$, is the correct identification of the real frequency positions for the components of the convoluted voltages. This identification lets us define the second band voltage vectors, $Vgs2_{Band}$, $Vgsds2_{Band}$ and $Vds2_{Band}$, which can be employed to calculate the convolutions with the derivative spectra, $Gm2(\omega)$, $Gmd(\omega)$ and $Gd2(\omega)$, by the classical conversion matrix multiplication.

$$
\begin{aligned}
&Ids^{NL}{}_{2Band} = Gm2_C.Vgs_{2Band} + Gmd_C.Vgsds_{2Band} + \\
&+ Gd2_C.Vds_{2Band} \qquad (4)
\end{aligned}
$$

III. DEVICE CHARACTERIZATION AND MODELLING

It has been shown that accurate mixer IMD calculations are only possible if the model is able of reproducing the nonlinearities' derivatives along the entire local oscillator excursion [11].

Recently, a global *Ids(Vgs,Vds)* model [9], valid for the linear and saturated regions, has been extracted from the measured FET derivatives. The model is based on the Shockley description, but introducing effective control voltages (Vgs_{eff} and Vgd_{eff}) with soft and controlled transitions to their values in pinch-off and forward conduction (see Fig. 3).

$$
Ids = Go \cdot \left\{ Vgs_{ef} - Vgd_{ef} - \frac{2}{3} \cdot \left[\frac{(\phi - Vgd_{ef})^{E+Ke.Vgd_{ef}} - (\phi - Vgs_{ef})^{E+Ke.Vgs_{ef}}}{(\phi - Vpx)^{1/2}} \right] \right\} \qquad (5)
$$

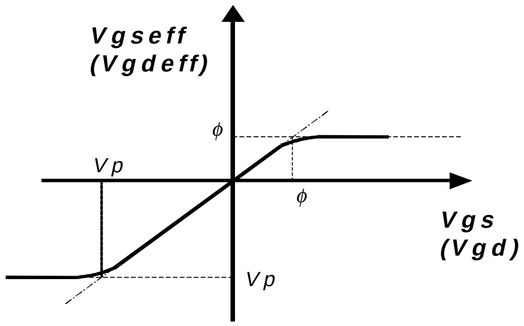
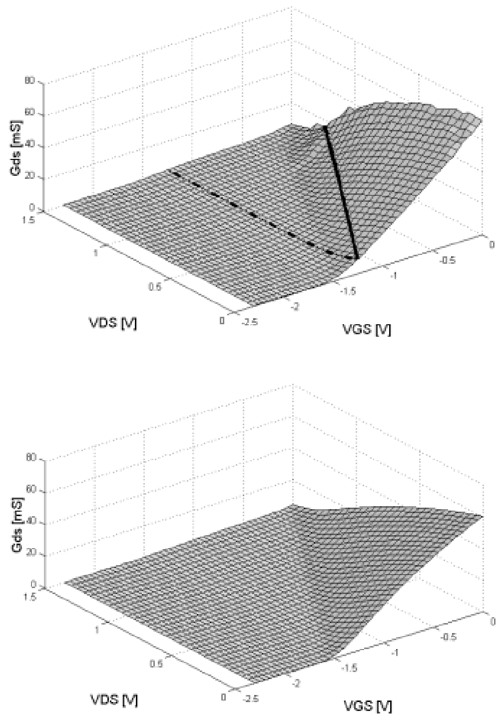


Fig.3 Effective control voltage definition

As a way of illustration, in Fig. 4 we show the measured and modeled output conductance for a typical MESFET device from GEC-Marconi, in its linear region. Results for the other *Ids(Vgs,Vds)* derivatives may be found in [9].

In the case of the measured *Gds*, two lines highlighting the *Gds* change of curvature (see [9]) are displayed. These lines could approximately be defined by $V_{GS} \approx Vp$ and $V_{GD} \approx Vp$, an important detail in the model conception.

The *Gds* reproduction over the whole range is very good. In a resistive mixer [12], whose linearity properties are highly appreciated, a good *Gds* (and its derivatives) reproduction in this range is determinant, especially for $V_{DS} = 0V$. Thus, an accurate IMD prediction could be expected if we could combine such a model with the proposed extended analysis technique.



a)

b)

Fig. 4 (a) Measured and (b) modeled *Gds*. The lines denote the set of bias points where *Vgs* and *Vgd* ≈ *Vp*.

IV. MULTITONE IMD EXPERIMENTS

The nonlinear current technique for multitone excitation was included in an in-house simulator to evaluate spectral regrowth and NPR in single FET mixer structures. A resistive mixer employing the characterized *6x50µm* F20 MESFET was designed, measured and simulated. The LO and RF frequencies were selected below *2 GHz* in order to avoid important IMD contribution from the reactive nonlinearities.

A. Spectral Regrowth

In Fig. 5, we show the simulated and measured values of the spectral regrowth appearing at the intermediate frequency (IF) for a LO signal of *1.6 GHz* and *0 dBm*, and a *1.7 GHz* QPSK RF signal. The input spectrum was discretized in *61* components whose phase relation was available. Such a large number of tones can be handled without problem thanks to the non-iterative nature of the Volterra-series approach. As can be appreciated, there is a very good agreement between both results.

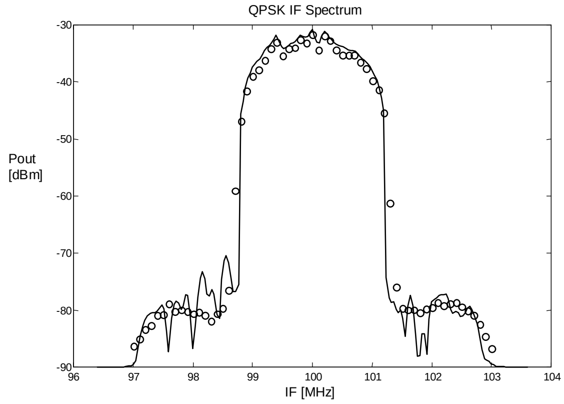


Fig. 5 Spectral regrowth prediction. Simulated (—) and measured (o o o) IF output amplitude spectrum.

B. Noise Power Ratio

In Fig. 6, we represent the IF output spectrum for a NPR experiment at similar frequencies. For the simulation, a discrete amplitude spectrum was generated from the NPR excitation, and different calculation results for a series of random phase distributions were evaluated and averaged. The predictions are quite similar to the measurements, validating our approach.

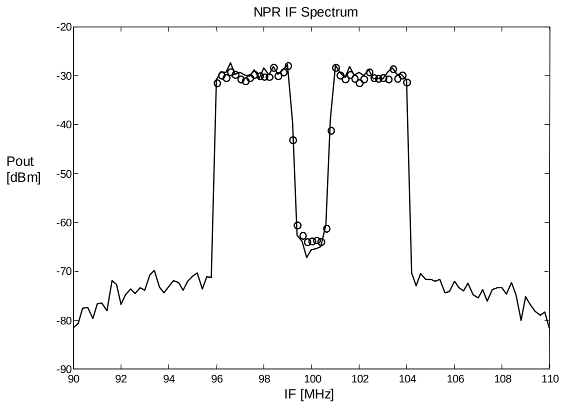


Fig. 6 NPR prediction. Simulated (—) and measured (o o o) IF output amplitude spectrum.

V. FROM MULTITONE TIME-VARYING TO MULTITONE TIME-INVARIANT ANALYSIS

The small-signal analysis of an amplifier under multitone excitation can be considered as a particular case of the same analysis for a mixer. It means, once we have developed an analysis tool for calculating IMD on mixer applications, where “the bias point” is LO time-varying, we are in position of doing the same for those applications where the bias point is fixed.

In order to validate our nonlinear analysis software and the previously referred model for this particular case, simulations and measurements were made on a class A amplifier built with the same transistor.

A. Spectral Regrowth

In Fig. 7, the simulated and measured output spectrum is presented. The input was also a *1.7 GHz* QPSK, but the device was operated in the saturation region. It is also appreciated that the spectral regrowth prediction is very good, supporting our approach.

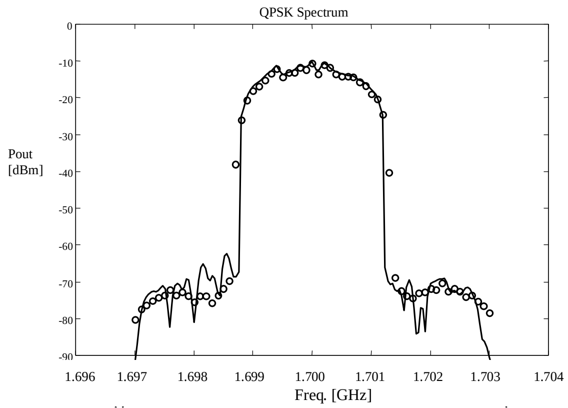


Fig. 7 Spectral regrowth prediction. Simulated (—) and measured (o o o) output amplitude spectrum.

VI. CONCLUSIONS

It has been shown that small-signal nonlinear distortion phenomena, such as spectral regrowth and NPR, can be efficiently predicted in FET mixers employing time-varying Volterra-series analysis along with a conveniently extracted model. The direct and non-iterative nature of the method determines a high degree of accuracy and the absence of convergence problems. The method is valid for narrowband modulated or wideband multicarrier RF signals, while the small-signal regime is guaranteed.

VII. ACKNOWLEDGEMENTS

The authors want to thank Prof. Almudena Suarez and Lic. Yolanda Newport for their help on the nonlinear analysis tool evaluation.

VIII. REFERENCES

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