

# Symbolic Distortion Analysis of Analog Integrated Circuits

Wim Verhaegen\* and Georges Gielen\*

**Abstract** — A technique for generating symbolic expressions for the distortion in weakly nonlinear analog integrated circuits is presented. This technique uses some acceptable assumptions to reduce the task of analyzing the nonlinear circuit to a repeated analysis of derived linear circuits. This repetitive algorithm has been implemented and it is demonstrated on an example circuit.

## 1 Introduction

In the analysis of analog integrated circuits, distortion and intermodulation are important factors. Either they are unwanted, as is the case in linear building blocks like opamps, or they are explicitly wanted to obtain a signal shifted in frequency, as is the case with mixers. Distortion and intermodulation need to be assessed accurately in both cases.

Classical numerical simulation techniques using iterative algorithms for solving the differential equations are slow and inaccurate due to the large difference between the time constants normally present in the circuits of interest. Several numerical methods have been developed to overcome this problem, e.g. the harmonic balance technique [1], multitime analysis [2] and the use of describing functions in circuits with feedback [3]. However, the numerical nature of these techniques implies that no symbolic results can be derived, so that re-use of results — in the form of design equations — is not possible.

An analysis technique that does yield symbolic results is described in this paper. Based on a set of assumptions, the analysis of a weakly nonlinear circuit is reduced to a number of analyses of linear circuits. A linear symbolic analysis core is used for these individual analysis steps, and its results are combined and manipulated to get a closed-form symbolic end result. This result can be used as a design equation, or the impact of the circuit nonlinearities on distortion and intermodulation can be derived from it.

Before explaining this technique, it is to be noted that similar approaches have been followed in the past to obtain symbolic expressions for the distortion in specific classes of circuits. E.g. the distortion in sampling mixers is analyzed in [4], and a method for analyzing the distortion in analog building blocks is presented in [5]. All symbolic approaches are intrinsically limited somehow, and these publications are no exceptions. The scope of the algorithm presented in this paper is limited to weakly nonlinear circuits. This means that the circuit

characteristics are nonlinear in a smooth way, implying that higher-order contributions are always smaller than lower-order ones, and that the applied signals are small.

The basic terminology used is explained in section 2, followed by a brief explanation of the algorithm in section 3. The implementation is demonstrated in section 4, and the conclusions are presented in section 5.

## 2 Terminology

The following terms are used in this paper:

- An  $n$ -dimensional conductance is a conductance with  $n$  controlling branch voltages. When analyzing analog integrated circuits,  $n$  equals 3 at most. The corresponding branch voltages are denoted as  $v_x$ ,  $v_y$  and  $v_z$  in this paper.
- A nonlinear current is described using its DC component and the derivatives to the controlling branch voltages. The derivatives up to order 3 are described by nonlinearity coefficients. E.g. the  $q$ 'th-order nonlinearity coefficient  $K_{g_1, g_2, g_3, \dots, g_q}$  of a three-dimensional conductance for  $q \geq 2$  is given by

$$\frac{1}{m!n!(q-m-n)!} \frac{\partial^q (v_x, v_y, v_z)}{\partial^{m-1} v_x \partial^{n-1} v_y \partial^{q-m-n} v_z} \quad (1)$$

where  $g_1$ ,  $g_2$  and  $g_3$  are the conductances through which the current controlled by respectively  $v_x$ ,  $v_y$  and  $v_z$  flows.

- The component of a signal at a frequency which is a linear combination of the input-signal frequencies, is denoted a phasor. E.g. the phasor  $V_{\text{linear}, \theta_1, 1, 1}$  is the component of the signal  $v_{\text{linear}, \theta}$  at frequency  $f_{\theta, 1} + f_{\theta, 2}$ . The signal  $v_{\text{linear}, \theta}$  is reconstructed from all corresponding phasors using the formula

$$v_{\text{linear}, \theta}(t) = \frac{1}{2} \sum_{m=-\infty}^{+\infty} \sum_{n=-\infty}^{+\infty} V_{\text{linear}, \theta, m, n} e^{j(\omega_m + \omega_n)t} \quad (2)$$

with  $\omega_x = 2\pi f_x$ .

## 3 Algorithm

The algorithm used for analyzing weakly nonlinear circuits is explained in [6]. Only the conclusions are given here for reasons of brevity. There is one basic formula for calculating a phasor:

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