A look-up table empirical model for the nonlinear dynamic performance prediction of microwave transistors

F.Filicori*, G.Vannini**, V.A.Monaco**

* Istituto di Ingegneria, Università di Ferrara, ITALY
** Dipartimento di Elettronica, Informatica e Sistemistica, Università di Bologna, ITALY

Abstract

This paper describes a mathematical model which has been adopted for the large-signal performance prediction of electron devices in the framework of Harmonic-Balance tools for circuit analysis.

The model, which is technology independent, is based on look-up tables storing small-signal bias/frequency-dependent AC parameters and DC characteristics obtained by means of conventional automated measurement equipment. The large-signal dynamic device response is predicted, directly from the measured data, through a Nonlinear Integral expression.

In the paper special attention will be given to practical aspects (e.g., accuracy limitations, numerical interpolation techniques, etc...). Experimental and simulated results which confirm the validity of the proposed modelling approach are also presented.

Introduction

Quite recently, different measurement-based purely mathematical modelling approaches [1..7] have been proposed for the large-signal performance prediction of microwave electron devices. The basic aim of these new approaches is that of providing a reliable, technology-independent predictive link between conventional measurements (e.g., measured static or "pulsed" DC characteristics plus small-signal bias/frequency dependent S-parameters or, equivalently, two-dimensional numerical device simulations), and Harmonic-Balance (HB) tools for nonlinear MMIC design. Mathematical models are interesting alternatives to conventional modelling approaches [8], where the dynamic phenomena in electron devices are described by lumped-element equivalent circuits and the nonlinear effects are represented through suitable special-purpose analytical functions.

Nonlinear equivalent circuits, despite their relatively good level of accuracy, have the drawback of requiring quite refined numerical and measurement procedures for parameter extraction, since the description based on lumped elements and analytical functions intrinsically implies approximations of the measured data. Optimisation-based parameter extraction procedures, in particular, may lead to values of the model parameters which are not unique (i.e., dependent on the initial values chosen in the optimisation algorithm) and, even, "not physical". Moreover, nonlinear equivalent circuits are technology-dependent models.

In this paper the basic features of a look-up-table-based mathematical model (NIM [1..4]) for the nonlinear dynamic performance prediction of microwave transistors are described. The model, which is technology independent, has been derived on the bases of nonlinear system theory by taking into account the particular features of electron devices. In particular, after considering the predictive capabilities and accuracy limitations of the closed-form Nonlinear Integral expression which has been adopted to describe the nonlinear device response at high frequencies, special emphasis will be given to the numerical model implementation. Experimental and simulated results will be also presented.

The look-up table empirical model

Look-up table empirical models require the storage of suitable data which provide a complete experimental characterisation of the electrical behaviour of an electron device under particular operating conditions. Usually these data, which can be obtained either from measurements or accurate physics-based numerical simulations [9], include small-signal bias/frequency-dependent AC parameters plus DC characteristics.

The device response under any given small-signal operating conditions can be quite easily obtained by means of suitable numerical interpolation techniques. In this context, look-up tables do not represent "strictly" a model since no *"predictive capabilities"* are involved.

As far as nonlinear modelling is concerned, beside interpolation techniques, also a "predictive link" is required to predict the large-signal dynamic behaviour of the device from data (i.e., small-signal bias/frequency-dependent AC parameters and DC characteristics) which have been measured under strongly different operating conditions.

In [1..4] it has been shown that the nonlinear dynamic current/voltage response of a two-port electron device can be accurately described, directly in terms of conventional measured data, by the following predictive expression for Harmonic-Balance circuit analysis:

$$\underline{i(t)} = \underline{F}^{DC}\{v_1, v_2\} + \sum_{n=-N}^{+N} \underline{\widetilde{Y}}\{v_1, v_2, \omega_n\}\underline{V_n}e^{j\omega_n t} \tag{1}$$

$$\text{with } \underline{\widetilde{Y}}\{v_1(t), v_2(t), \omega_n\} =$$

$$= \underline{Y}\{v_1(t), v_2(t), \omega_n\} - \underline{g}^{DC}\{v_1(t), v_2(t)\} \tag{2}$$

where $\underline{i} = |i_1 \ i_2|^T$, $\underline{V_n} = |V_{1_n} \ V_{2_n}|^T$, $\underline{\widetilde{Y}} = \{\widetilde{Y}_{ij}\}$, $\underline{F}^{DC} = |F_1^{DC} \ F_2^{DC}|^T$, $\underline{Y} = \{Y_{ij}\}$, $\underline{g}^{DC} = \{g_{ij}^{DC}\}$.

Equation (1) is an integral-like expression (Nonlinear Integral Model [3]) since the computation of the device currents $i_1(t)$, $i_2(t)$, involves not only the instantaneous values of the applied voltages $v_1(t)$, $v_2(t)$, but also their spectral components V_{1_n}, V_{2_n} at the angular frequencies ω_n.

The functions $\widetilde{Y}_{ij}$ in (1), represent **nonlinearly voltage-controlled dynamic admittances** which can easily be computed [3], according to eqn. (2), in terms of conventional small-signal admittance parameters Y_{ij} and DC differential conductances g_{ij}^{DC}, measured[1] for different bias conditions in the frequency range of interest. The nonlinear dynamic admittances give a purely dynamic contribution to the currents i_1, i_2, since, according to eqn. (2), in DC operation $\widetilde{Y}_{ij} = 0$ and the device response coincides with the measured DC characteristics F_1^{DC}, F_2^{DC}.

In practice, only a "discrete" characterisation of an electron device in the space of the controlling variables $v_1(t)$, $v_2(t)$, ω_n can be carried out (i.e., the DC characteristics, including also the DC differential conductances, and the AC parameters are measured, or computed using physics-based numerical simulations, for a discrete set of bias conditions and frequencies). The measured data are stored in look-up tables which are used together with suitable interpolation algorithms to compute the values of the nonlinear dynamic admittances for each set of the controlling variables $v_1(t)$, $v_2(t)$, ω_n, occurring in the Harmonic-Balance analysis. On such a basis, eqn. (1) can be directly used to predict the large-signal dynamic response of the electron device.

An important property of the Nonlinear Integral Model (1) is that of being intrinsically exact in DC operation and under small-signals; in such conditions, in fact, the model simply coincides, respectively, with the measured DC characteristics and admittance parameters.

As far as the accuracy of (1) for the prediction of the device nonlinear dynamic response is concerned, a few considerations are needed. Equation (1) has been derived on the bases of nonlinear system theory by considering particular features of electron devices [3]. The basic assumption, which is justified both by experimental results and physics-based numerical simulations, is that the duration of nonlinear memory effects in an electron device is much shorter than the inverse of the typical voltage bandwidth in analog applications. In particular, eqn. (1) is the first term of a more complex multidimensional integral series which represents a rigorous, general model for nonlinear dynamic systems. It can be shown, that the truncation error Δi, introduced by neglecting in (1) the higher-order terms, can be expressed (for simplicity a single-port device is being considered) in the following form:

$$||\Delta i|| \leq \sum_{k=2}^{\infty} H_k(\mathcal{S}_F V_{pp} B \tau_E)^k \tag{3}$$

where V_{pp} and B are, respectively, the peak-to-peak value and the frequency bandwidth of the voltage applied to the device, while $\mathcal{S}_F$ is a *"shape factor"* which characterises the voltage waveform. In (3), H_k and τ_E characterise the importance of the purely nonlinear dynamic phenomena associated to the memory effects in a given device. In particular, τ_E represents an *"equivalent duration"* of these effects.

For a given electron device (i.e., given H_k and τ_E) and for a given shape of the voltage waveform (i.e., given $\mathcal{S}_F$), it can be always found a value of the product $V_{pp}B$ which makes the truncation error Δi negligible. In other words, the accuracy of the model is dependent on a compromise between the peak-to-peak value and the bandwidth of the applied voltages. It must be observed that the truncation error decreases at least quadratically with the factor $V_{pp}B\tau_E$. Experimental and simulation results [1..4] have confirmed the accuracy of the model (1) in typical microwave applications; in fact, the equivalent duration τ_E of the nonlinear memory effects in the device, is usually small enough to make the truncation error (3) negligible for the values of the product $V_{pp}B$ normally encountered in

[1]Admittance parameters can be obtained from S-parameters, which are more conveniently measured at microwave frequencies, by means of simple matrix transformations.

nonlinear microwave circuits.

In order to verify the accuracy properties of the NIM, the same large-signal amplifier, using an X-band GaAs MESFET, was analysed both by using the NIM, and two-dimensional drift-diffusion device simulations. In Fig. 1, constant error loci, associated to maximum discrepancies of 2% and 5% between instantaneous values of the drain currents computed from the above simulations, are plotted as functions of the peak-to-peak gate-to-source voltage and the power source frequency. The operation of the amplifier was, for all of the performed simulations, strongly nonlinear (the gain compression associated goes from a minimum of 2dB at 20GHz up to more than 7dB at 2GHz). Fig. 1 points out that the accuracy of the NIM is mainly dependent on a compromise between voltage amplitudes and operating frequency. In other words, the same level of accuracy can be obtained at higher frequencies if the amplitude of the voltages (i.e., the level of nonlinearity) is reduced.

Model implementation in HB tools

One of the key points when using look-up-table-based models is related to the associated interpolation algorithms.

The choice of the interpolation method for the NIM is not very critical, in the sense that particular properties of regularity (differentiability) are not required. This is due to the "smoothing" properties of the Fourier Transform algorithms which are used in the HB analysis to represent the frequency-domain response of active devices[2]. Thus, conventional piecewise-linear interpolation techniques [10] can be adopted. However, the choice of a higher-order "smooth" interpolation method which can correctly describe the bias-dependent admittances, can considerably improve the accuracy of the NIM (or any other look-up table model), without the need for increasing the refinement[3] of the "discretisation grid" used for model characterisation.

Numerical interpolators for look-up table electron device models should meet requirements which are usually not completely satisfied by conventional interpolating functions (e.g., splines). A suitable interpolation algorithm should not only provide "smooth" functions, at least once differentiable, passing trough the given set of measured values (e.g., the measured samples of the DC characteristics), but should also take into account the gradients of the nonlinear characteristics, which play an important role in analog circuit simulation. In practice, a good interpolator should satisfy exactness constraints also on the function gradient (e.g., small-signal conductance parameters) which is provided by small-signal measurements. Moreover, since electron device characteristics are strongly nonlinear, an "optimal" interpolation algorithm should be necessary "sectionwise" and "strictly local"[4]. This is important in order to avoid non-physical oscillations which may occur, for instance, in the strongly nonlinear transition between the conduction and non-conduction region of semiconductor junctions when using conventional splines [7].

In order to satisfy the above mentioned requirements, different approaches based on a strictly local low-order polynomial interpolator involving constraints both on measured function values and their gradients have been adopted. In particular, two slightly different approaches, based on almost quadratic and 3rd order Hermitian functions have been tested. As an example, in Fig. 2, the measured and interpolated current/voltage characteristic of a junction diode are shown; it can be noted that the "interpolating functions" adopted provide a "smooth" curve without the oscillating behaviour which, according to [7], can be found when using conventional splines (which are not strictly local).

Fig. 3 shows the differential conductances associated, respectively, to the measured data and the interpolating functions which satisfy also exactness constraints on the function gradient.

As a final remark concerning the CPU time required to compute the NIM response (1) in the framework of HB analysis programmes, it can be said that the computing effort required by the NIM is on the same order of magnitude as for equivalent circuit models. The time needed to compute the instantaneous values of the dynamic admittances $\widetilde{Y}_{ij}$ is, in fact, practically negligible if computationally efficient interpolation algorithms are adopted.

[2] In fact, it can be easily shown that any k-th harmonic component I_k of the current $i(t) = f\{v(t)\}$ is a continuos and differentiable function of any p-th harmonic component V_p of $v(t)$, even when the nonlinear function f is continuos, although not necessarily differentiable.

[3] In this case, a reduction of the amount of computer memory required to store the NIM data-set is also obtained. In any case, however, the dimension of the data-set, which is usually on the order of some hundreds of Kbytes, does not represent a problem for the modern workstations.

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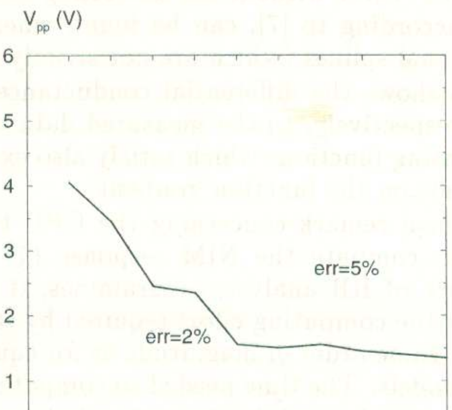

Figure 1: Constant error loci associated to maximum discrepancies of 2% and 5%, between the instantaneous values of the drain currents predicted by the NIM and drift-diffusion simulations, for a GaAs MESFET large-signal amplifier. The loci behaviour shows that the accuracy of the NIM is dependent on a compromise between the peak-to-peak voltage amplitude V_{pp} and operating frequency.

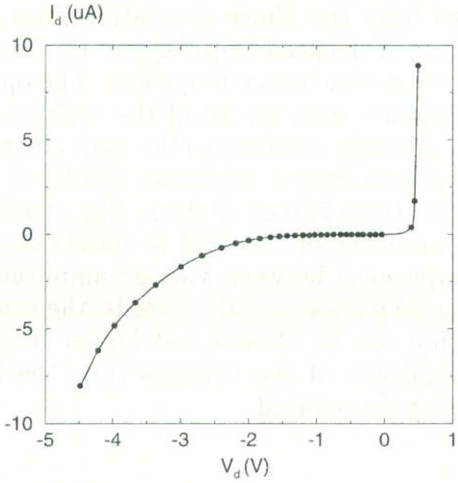

Figure 2: Measured (•) and interpolated (—) current characteristic for a junction diode. The strictly local interpolation was carried out both by using almost quadratic and 3rd order Hermitian functions (the results are practically coincident) which do not show "non physical" oscillating behaviour.

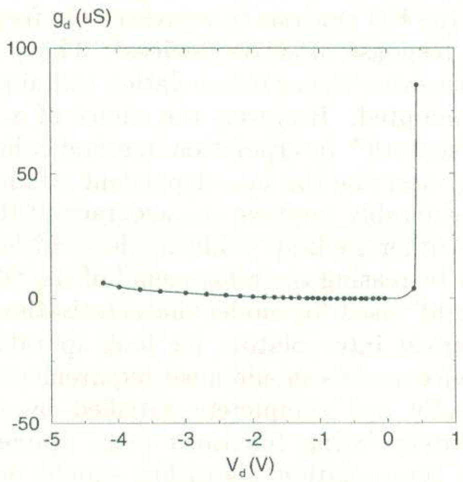

Figure 3: Differential conductances associated, respectively, to the measured data (•) and the interpolating functions (—) which satisfy also exactness constraints on the function gradient.