Frequency domain-based extraction method of one-port device's non-linear state functions from large-signal measurements

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Abstract — **A novel frequency domain-based method for the extraction of one-port device's non-linear constitutive relations directly from vector large-signal measurements is presented. A distinctive characteristic of the method is that it provides directly the charge-voltage state-function, without the need to perform the integration of the capacitance-voltage function as required by its time domain-based counterpart. The capabilities of the method are demonstrated by extracting the non-linear state-functions of a microwave diode from large-signal data generated by harmonic balance analysis, and the non-linear gate-source state-functions of a HEMT device under 'cold-FET' bias conditions from measured data.**

I. INTRODUCTION

The availability, in recent years, of vector large-signal measurements at microwave frequencies has paved the way to new research possibilities in the field of non-linear microwave solid-state device modelling. One of these possibilities is the extraction of device's non-linear constitutive relations, or state-functions, directly from large-signal measurements.

Different authors have successfully addressed this extraction problem in the last decade [1-14] but in almost all cases the extraction procedure was formulated in the time domain. Most of the successful methods developed today, for extracting the quasi-static (or memoryless) nonlinear state-functions of microwave one-port solid-state devices, are derived from the one proposed by Schreurs et al. [4] in 1996.

This time domain method [4] allows the separation of the component associated to conductive phenomena from the one associated to the storage of charge. It also provides the I-V and C-V characteristics, from which the state-functions for the nonlinear element are derived.

Although, as pointed out in [7], the extension of this approach to the two-port case is not straightforward, in recent years different methods [7, 9-12, 14] have been proposed that effectively address the bidimensional case. Note that the formulation is, in all cases, a time domain-based one.

Frequency domain formulations have been discussed by Schreurs et al. [6 ,8], but no working method has been proposed so far. The interest of frequency domain-based methods derives from the possibility of directly extracting, from large-signal measurements, the charge-voltage state-function, instead of the incremental capacitance-voltage function as time domain-based methods do.

This communication describes a novel method to directly extract the constitutive relations of one-port non-linear quasi-static devices. The novelty of the method relies on the frequency-domain formulation, and the fact that this allows the direct extraction of the Q-V relation instead of the C-V relation.

The validity of the method is illustrated by means of two examples. The first example is the characterization of a diode from simulated data that have been derived using the harmonic balance method. The second example provides the characterization of the gate-source constitutive relation of a HEMT device under 'cold-FET' bias conditions (V_{DS}=0) from VNNA (Vectorial Network Nonlinear Analyzer) large-signal measurements.

Although this communication only provides the description of the method for one-port devices, an extension of the method for two-port devices is under development.

II. THE METHOD

The proposed frequency domain-based extraction method relies upon the fact that even and odd components of the waveforms originated by a memoryless non-linear state-function under periodic excitation are not independent. In fact, odd components can be computed from the even ones (imaginary and real parts, respectively, of Fourier coefficients) and vice versa, provided the excitation is known. The details of the demonstration of this key relation are not given here for the sake of brevity.

To describe the proposed large-signal extraction method, consider the simple one-port network shown in Fig.1. It consists of the parallel connection of a memoryless non-linear conductance $i_g(v)$ and a memoryless non-linear capacitance $q(v)$.

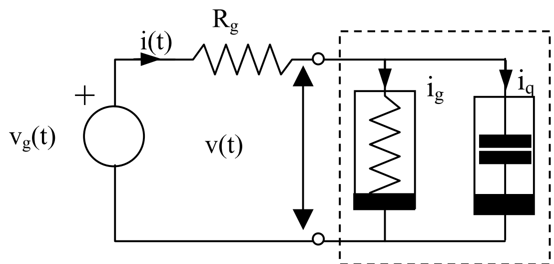

Fig. 1. One-port non-linear circuit.

The total current entering the network is given, in the time domain, by

$$i(t) = i_g(t) + \frac{dq[v(t)]}{dt} \quad (1)$$

If the response of the network to a single tone input signal is periodic (of period T_0), the above equation can be written, in the frequency domain, as

$$I_k = I_{g,k} + j\omega_0 Q_k \quad (2)$$

where I_k, $I_{g,k}$ and Q_k are the Fourier coefficients of $i(t)$, $i_g(t)$ and $q(t)$, respectively, with $\omega_0 = 2\pi / T_0$. This equation shows that, if N harmonics are taken into consideration, there are N complex equations (DC component excluded) and $2N$ complex unknowns, as discussed by Schreurs et al. [6, 8]. Therefore it could be concluded that coefficients $I_{g,k}$ and Q_k can not be determined from this kind of measurements [6, 8].

However, if the link between the odd and even components of the waveforms is taken into account, equation (2) will still have N complex equations but only $2N$ real unknowns. Therefore $I_{g,k}$ and Q_k can be obtained directly from the measured Fourier coefficients I_k of $i(t)$ by using, for instance, a VNNA system, provided that the Fourier coefficients V_k of $v(t)$ are also measured.

III. APPLICATION OF THE METHOD

A. Simulated data

To illustrate the performance of the method, and as a first example, the extraction of the simple one-port network shown in Fig. 1 has been performed. In this circuit the non-linear conductance has a conventional 'exponential' non-linear I-V relationship, and the non-linear capacitance has been defined by its incremental capacitance function $C(v) = c_0 v^2$, with c_0=100 pF/V^2, so that $i_g(t) = C(v)\frac{dv(t)}{dt}$.

Measurements under large-signal regime have been simulated analysing, by means of harmonic balance with 10 harmonics, the response of the circuit to the injection of a 1 GHz signal (amplitude 0.25 V, DC component 0.8 V, R_g=1 Ω). Results using the proposed extraction method are shown in Figs. 2 and 3.

Notice that, regarding the results shown in Fig. 3, the output of the method is directly the charge-voltage constitutive relation. The curve in Fig. 3 labelled as 'model' corresponds to the computed q-v relation from $C(v)$ and given by $q(v) = \frac{c_0}{3} v^3 + q_0$, and the q-v state-function extracted from the large-signal 'measurements', labelled as 'extracted' fits almost exactly the 'model'.

The agreement between extracted and modelled non-linear state-functions can be considered excellent, which proves the validity of the proposed large-signal extraction method.

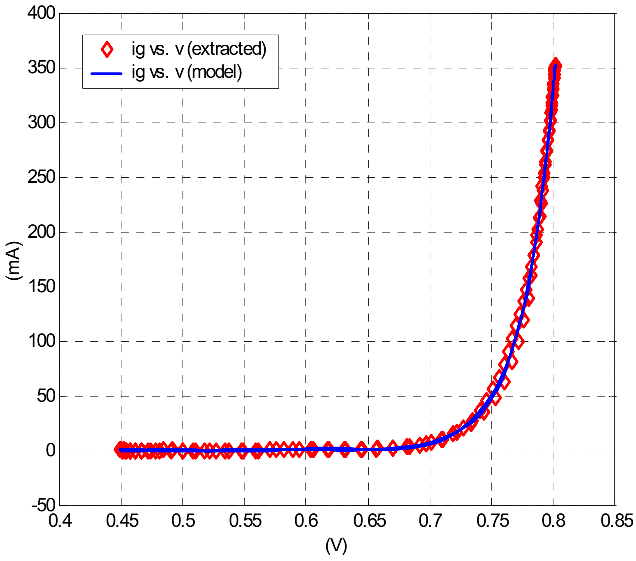

Fig. 2.- Extracted and modelled non-linear conductance state function (simulated diode).

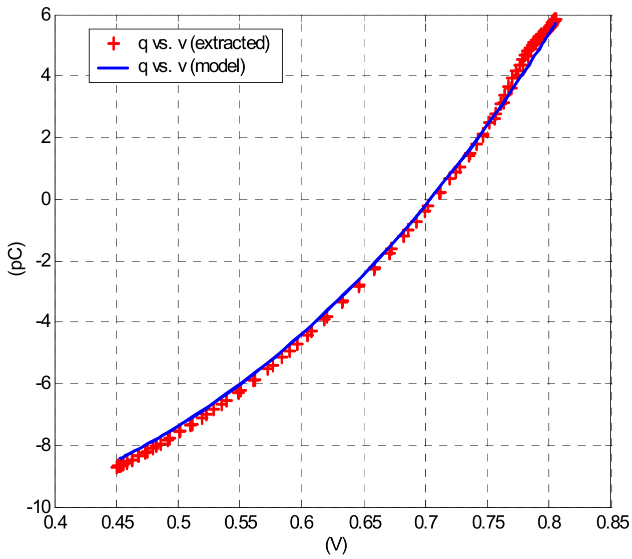

Fig. 3.- Extracted and modelled non-linear capacitance state function (simulated diode).

B. Measured data

In a second phase, with the purpose of illustrating the performance of the method under real experimental conditions, the constitutive relations of the circuit defined by the gate to source port of a HEMT device biased under 'cold FET' conditions (V_{DS}=0) [10] have been extracted.

The VNNA measurements used [10] include information of magnitude and phase up to the 10th harmonic, being the frequency of the input signal 2 GHz. Fig. 4 plots the intrinsic gate current versus the intrinsic gate to source voltage, after properly de-embedding the extrinsic elements. This trajectory, obtained by using a simplified extrinsic structure, is similar to the one presented in [10]. It shows the clear non-linear behaviour, but also the existence of a strong capacitive component in the current.

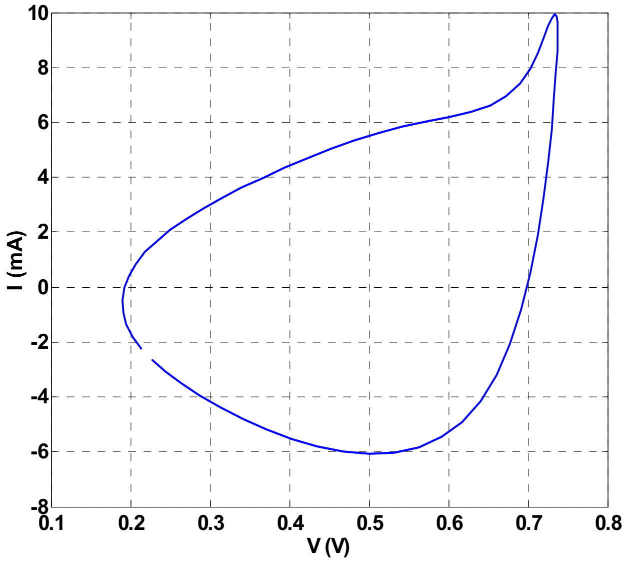

Fig. 4.- Measured $i_g(t)$ versus measured $v_{gs}(t)$ under large-signal regime.

If it is assumed that this non-linear one-port circuit is quasi-static and that no low frequency dispersion effects are present, a non-linear model can be built by the parallel combination of a non-linear conductance and a non-linear capacitance, which corresponds to the model depicted in Fig.1. Therefore, the proposed method can be directly applied to the characterization of this non-linear circuit. Results obtained using the new method are shown in Figs. 5 and 6.

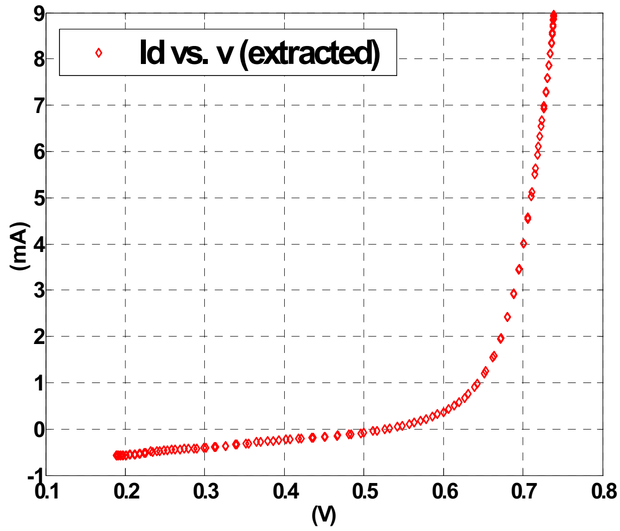

Fig. 5.- Extracted non-linear conductance (I-V) state-function (measured HEMT)

The extracted conductance constitutive relation is similar to the one obtained using the time domain-based method described in [10].

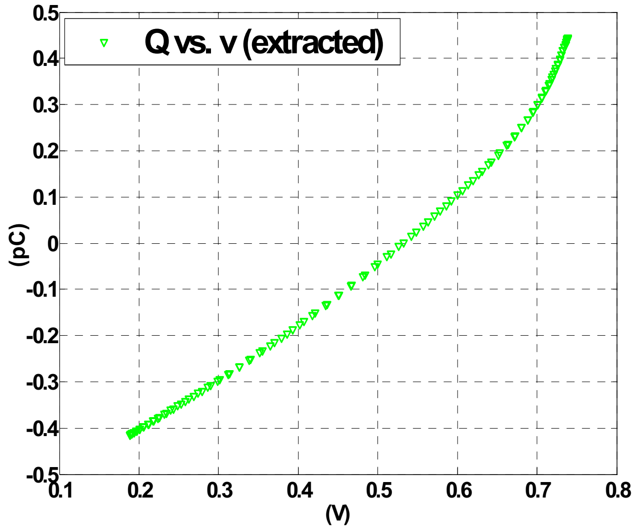

Fig. 6.- Extracted non-linear charge generator (Q-V) state-function (measured HEMT).

The extracted non-linear charge generator state-function allows the incremental capacitance to be easily computed by deriving the state function with respect to the control voltage. The computed incremental capacitance has been plotted in Fig. 7. The obtained capacitance notably matches the one described in [10].

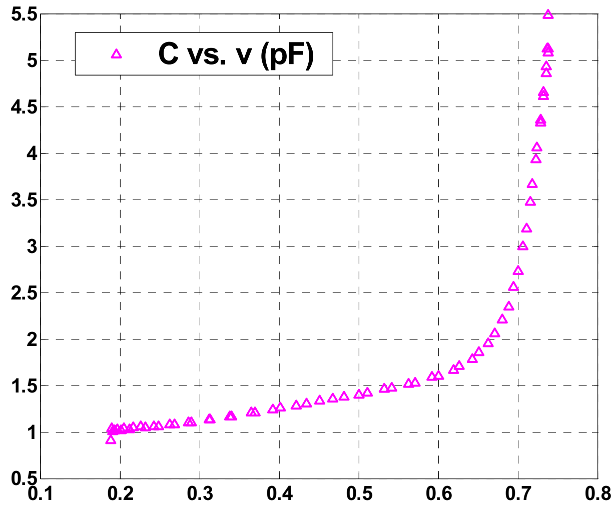

Fig. 7.- Non-linear capacitance (C-V) function computed from the extracted non-linear charge generator (measured HEMT).

These results lead to the conclusion that the proposed method not only is a valid method, but also it is sufficiently robust to errors in the measurements due to the accuracy of present instrumentation.

IV. Conclusions

A novel frequency domain-based method to extract one-port device's non-linear constitutive relations directly from vector large-signal measurements has been presented. This frequency domain-based method provides directly the device's Q-V constitutive relation. Consequently it does not require the integration of the C-V relation as needed by time domain-based methods. Both simulated and real measurements have been used to evaluate the performance of the method. Examples presented and analysed have demonstrated the validity of the method and its robustness to errors in the measurements. The extension of the method to two-port devices is being developed at present.

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