Validation of a Behavioral Model based on Volterra Series with coefficients determined orthogonally

Abstract — **This paper presents some validation results of the behavioral modeling capabilities of the Volterra Series extracted orthogonally to model systems represented by different topologies. Two different systems are considered: a nonlinear system with linear memory and a nonlinear system with nonlinear memory. In both situations the proposed approach presents good results.**

I. INTRODUCTION

Behavioral modeling of Power Amplifiers (PAs) for wireless communications systems is very useful for performance improvement in system level simulations. When circuits with a high number of active elements are considered the use of a behavioral model instead of a circuit level based model can reduce significantly the computational effort required to compute the system's response. Also the behavioral models can represent accurately one system without giving any information of its components so it is also used as a form of intellectual property protection by circuit/system fabricants.

Due to the previously presented advantages, the behavioral models of PA are very useful for testing and implementing Digital Pre Distorters (DPDs).

Due to its importance the behavioral model field has been quite active in past years, with many new empirical approaches to achieve different model topologies. The authors of this paper proposed a systematic approach based on system identification theory to obtain a model with guaranteed prediction capabilities and to optimally determine its coefficients. In this paper the model topology and coefficient determination procedure are validated considering two different examples of amplifiers to be modeled.

Section II of this paper presents some references to previously published papers which describe the model basis and formulation. In Section III the two systems used for model validation are described and characterized, while in Section IV the modeling results are presented. Finally, in Section V some conclusions are drawn.

II. MODEL FORMULATION

The modeling approach herein presented is founded on the rigorous nonlinear system identification theory. This states that any single-input / single-output nonlinear dynamic system that is stable and of fading memory, can be represented by a cascade of a single-input multiple-output linear system with memory, followed by a multiple-input single-output nonlinear memoryless system [1,2]. One possible implementation of this is the nonlinear finite impulse response filter stated in (1).

$$y(s) = f_{NL}\left[x(s), x(s-1),..., x(s-M)\right] \quad (1)$$

In this expression M, indicates the number of time delays considered (the system's memory span or depth) while $f_{NL}(.)$ is any $(M+1)$ to 1 nonlinear universal approximator. Two widely used implementations of this universal approximator are the artificial neural network (ANN) – which leads to the time-delay ANN nonlinear filter, and the multidimensional polynomial – leading to the general polynomial filter (PF) or Volterra filter [3]. In this work the model adopted was the Volterra series and a procedure for orthogonal coefficient extraction was developed has presented in [4]. It is necessary to stress out that the orthogonality condition is verified only for a particular situation of a predefined input signal statistics and power. For this input point the model coefficients are extracted and are then valid under a given range near this point. The model's validity range depends on the degree and type of nonlinearity of the system. In a general situation, the model should be valid in a large enough range to be considered useful.

The input signal type chosen for the orthogonal extraction of the coefficients was a multisine of equal amplitudes, equally spaced tones and random phases. It was proved [5] that the statistical ensemble of a large number of randomized phase realizations of this multisine has the same properties of band-limited white Gaussian noise. The details of the orthogonal model extraction procedure can be found in [4,6].

III. SYSTEMS FOR MODEL VALIDATION

To validate the proposed modeling approach, two classical types of systems will be used: *a*) the Wiener-Hammerstein cascade and *b*) a nonlinear amplifier with memory. The two test systems were implemented in ADS as virtual circuits and then the behavioral model were extracted in Matlab. As described in the previous section, the model coefficients were extracted using a set of multisines with randomized phases. The model coefficients were then used to predict the system's response to a WCDMA signal and the normalized mean square error (NMSE) between the predicted and measured outputs is calculated.

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A. Characterization of the Wiener-Hammerstein system.

The Wiener-Hammerstein system is represented in Figure 1.

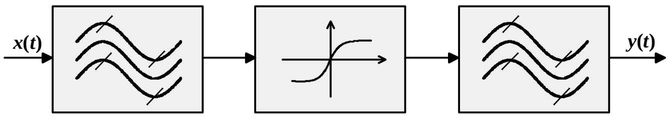

Fig. 1. Schematic representation of the Wiener-Hammerstein system.

This system has an input and output filter which confine the signal to a certain desired bandwidth, and a nonlinear static amplifier that introduces some static distortion. This is a good block diagram to represent a wireless communication transmitter of narrowband signals (i.e., the ones for which the bandwidth is much smaller than the center frequency).

The following figures present the characterization of the system in terms of linear memory (in the small signal regime) and nonlinearity.

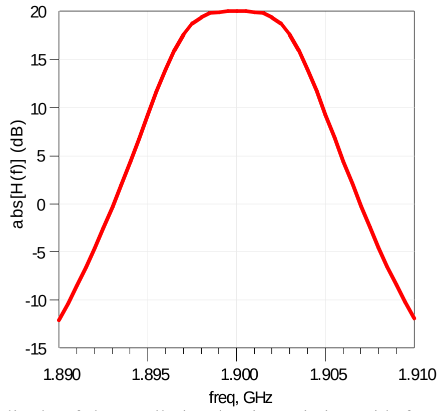

Fig. 2. Amplitude of the small signal gain variation with frequency of the considered Wiener-Hammerstein system.

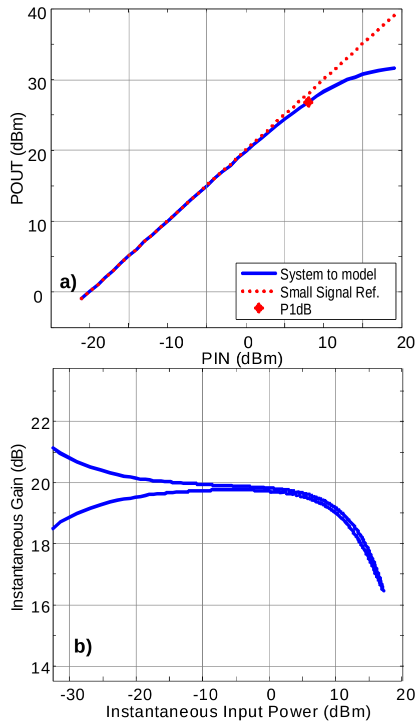

Fig. 3. a) One tone average P_{IN}/P_{OUT} of the system of Figure 2. b) Instantaneous two-tone Gain curve for the Wiener-Hammerstein configuration.

B. Characterization of the Nonlinear Amplifier with Memory

The other system considered, a nonlinear amplifier with memory imposed by a feedback loop, can be represented by the block diagram of Figure 4.

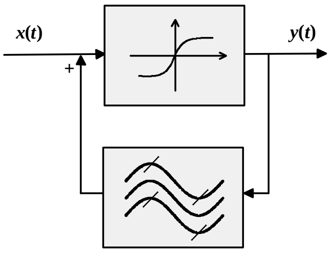

Fig. 4. Schematic representation of the Hammerstein model configuration.

In this case, and on the contrary to the previous situation, the nonlinearity and memory are entangled in a way that they cannot be represented by any cascade of independent blocks. This also means that there are some memory effects that are only visible when the nonlinearity is active. The presence of nonlinear memory is one of the most difficult aspects to consider in behavioral modeling, since the effects of this memory are only visible in some particular situations. Thus, to capture such behavior the selection of adequate stimuli is mandatory.

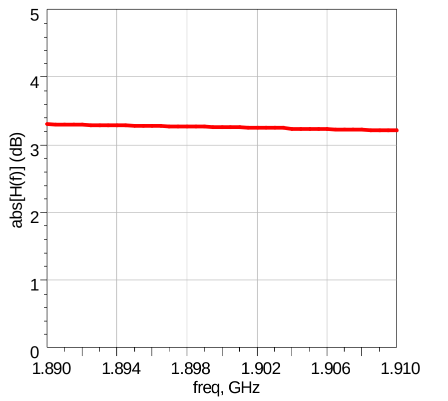

Fig. 5. Amplitude of the small signal gain variation with frequency of the nonlinear amplifier with memory considered.

The differences between linear memory of both systems are stressed in Figures 2 and 5. While the Wiener-Hammerstein system presents a clear bandpass response, the other system presents a flat amplitude transfer function. (The phase characteristics are not shown in this paper due to lack of space). The nonlinear characteristic of the systems is shown in figures 3a) and 6a), where it can be seen their similar compression characteristics, with the 1dB compression point of the system B slightly above.

The dynamic AM/AM plots shown in figures 3b) and 6b) point out the linear memory of the Wiener-Hammerstein system in the curve opening for small input power, and the nonlinear memory of the system b) on the opening of the curve at the higher input power zone.

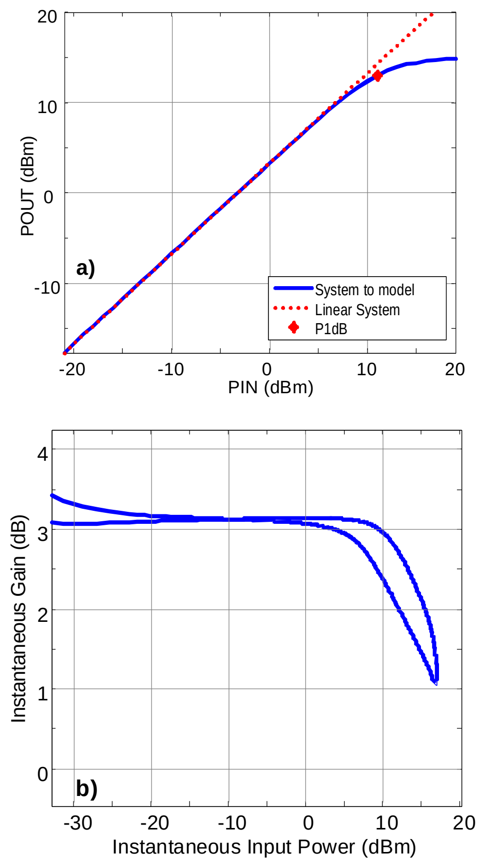

Fig. 6. a) One tone average P_{IN}/P_{OUT} of the system of Figure 2. b) Instantaneous two-tone Gain curve for the Wiener-Hammerstein configuration.

To circumvent potential practical limitations on the number of extracted coefficients and of signal time samples required to represent a real communications' system, a lowpass equivalent model formulation will be used. This way, the number of time samples required decreases substantially since the sample frequency is chosen to verify the Nyquist criteria for the signal's bandwidth and not for the carrier frequency.

For both of these systems the nonlinear model is extracted with five tones up to fifth order. The number of delays was selected observing the systems' impulse response and selecting the number of samples that contain the most significant part of its energy. A fifth order nonlinearity is a good compromise between accuracy and complexity, since a third order system might be a poor approximation and a seventh order one becomes two complex. The modeling results achieved are shown in the next section.

IV. MODEL RESULTS

In this section the model approximation results are evaluated in both the systems described in section III. To evaluate the models' accuracy, we used comparison plots of the model and system responses to: (i) a single tone input/output power sweep; (ii) the spectra of the output of a WCDMA signal and (iii) the variation of NMSE between modeled and measured WCDMA output signals with the variation of the input average power.

A. Wiener-Hammerstein System

Figure 7a) presents the comparison of input/output power sweep obtained in a static way using a single-tone excitation. Figure 7b) shows the measured and modeled complex envelope of the WCDMA signal used to perform the cross validation of the model, and Figure 7c) presents the variation of the NMSE for the Wiener-Hammerstein system model with the input power level variation. The model's local behavior is once again visible on this figure. In figures 7a) and c) the local behavior of the model is visible. Actually, the divergence seen for high powers is due to the polynomial nature of the model.

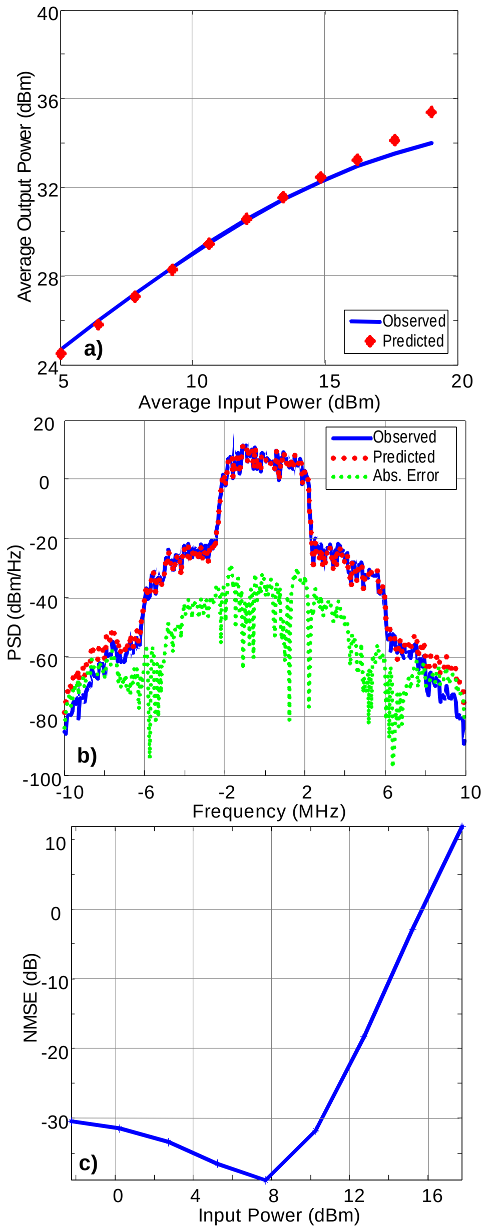

Fig. 7. Comparison of model and system responses. a) one tone PIN/POUT. b)WCMA spectra comparison. c) NMSE variation with average input power sweep for a WCDMA input stimuli.

In Figure 7c) it is seen that for an input power of approximatelly 8 dBm (~1dB compression point shown in

Figure 3a) the NMSE between model and system outputs is better than – 35dB, which is a very good result for this level of nonlinearity and for a cross-validation experiment.

B. Amplifier with Nonlinear Memory.

Figure 8 presents the same validation experiments as in the previous example. Once again it is visible the model degradation when the input power increases (however the model gives resoanable results for power levels of up two 5 dB above the 1dB compression point – compare figures 8a) and 6a)).

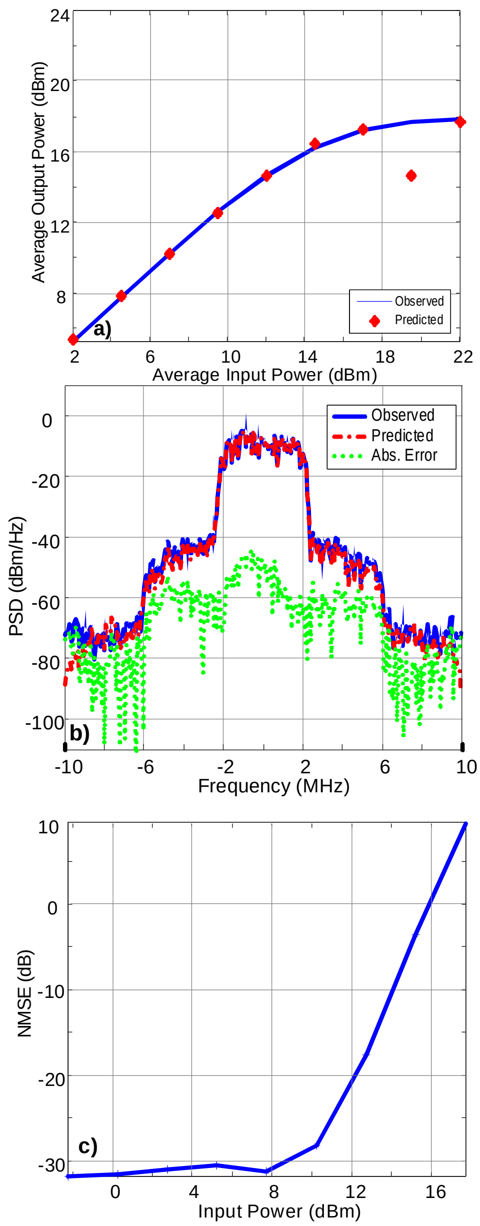

Fig. 8. Comparison of model and system responses. a) one tone PIN/POUT. b)WCMA spectra comparison. c) NMSE variation with average input power sweep for a WCDMA input stimuli.

This situation, as was previously refered, is hard to model due to the memory effects that are only visible in the presence of nonlinearity Thus the model performs not as good as in the previous example. Yet, a NMSE bellow -30 dB is still visible in Figure 8b).

V. CONCLUSION

The modeling approach previously presented in [4,6] was here validated with two different types of systems and the results obtained are quite satisfactory. Even in the hard situation of a nonlinear system with nonlinear memory an NMSE better than -30dB was obtained.

The utilization examples presented in this paper are an indication of the usefulness of the previously proposed model.

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