산업체 기고문

Measurement-Based Large-Signal Simulation of Active Components from Automated Non-Liner Vector Network Analyzer Data via X-parameters

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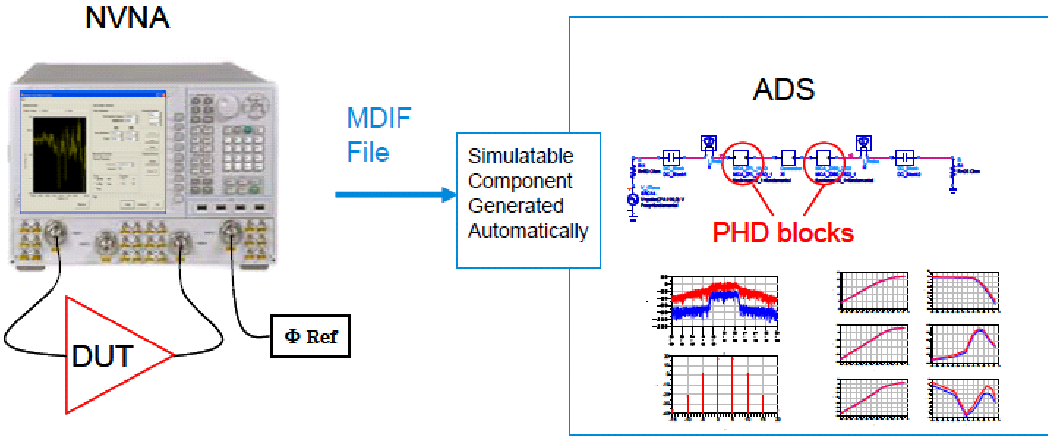
Ⅰ. Introduction

X-parameters are mathematically rigorous supersets of S-parameters, applicable to nonlinear (and linear) components under both large-signal and small-signal conditions. X-parameters include the magnitude and phase characteristics of device-generated spectral components corresponding to distortion, which can include harmonics and intermodulation products, in addition to those spectral components present in the incident signal. X-parameters represent both the nonlinear characteristics of the DUT due to a large-signal stimulus, and also the spectrally linearized response around the large-signal state of the system to additional injected signals, that now depends nonlinearly on the DUT operating conditions that are determined by the large-signal excitation. X-parameters can be used to calculate the effects of mismatch at fundamental and harmonic frequencies, and correctly predict effects of source harmonics on DUT response. This paper describes how to measure X-parameters of nonlinear components with appropriate new hardware and measurement algorithms, encapsulate the data into a nonlinear mathematical framework, and design nonlinear systems with this data in a modern CAE simulator environment. Each piece (measurement, mathematical formalism, and simulation) of the puzzle has been created, they are now commercially available, and they fit together seamlessly. This results in an automated, high-throughput, interoperable system for predictable measurement-based nonlinear design with X-para- meters[4]. This work demonstrates, for the first time, the quantitative superiority of the X-parameter approach to that of 'Hot S-parameters' for the design of a cascaded system of two imperfectly matched amplifiers under large-signal drive.

Ⅱ. Interoperable Nonlinear Measurement and Large-Signal Simulation

The measurement apparatus is a new Agilent Nonlinear Vector Network Analyzer (NVNA) capable of nonlinear calibration and measurements similar to [8]. The NVNA is based on a PNA-X dual-source network analyzer with a special InP IC phase reference comb generator for cross-frequency phase calibration[5] and



[Fig. 1] Simplified configuration for NVNA and PHD blocks in ADS for simulation and design with measured X-parameter nonlinear component data.

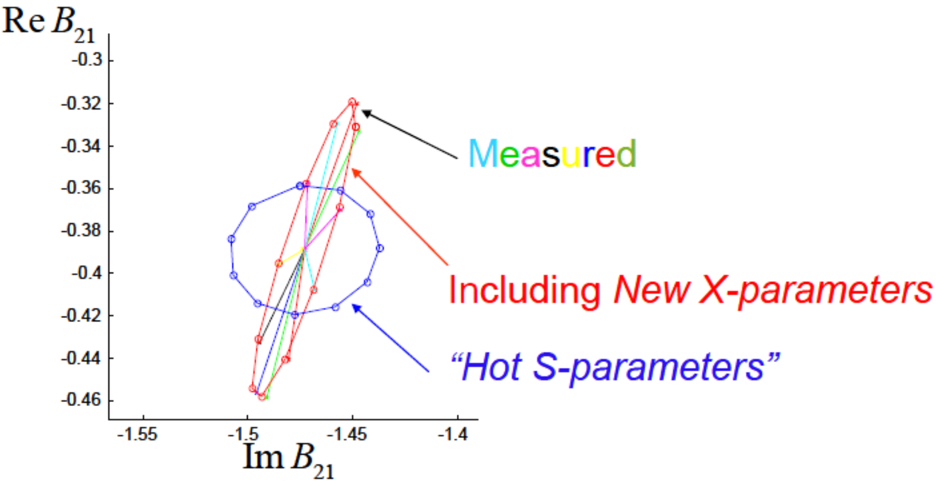
special NVNA application software and interface for instrument control with built-in support for highly automated X-parameter characterization and extraction. The X-parameter measurement methodology reported here uses a large-signal stimulus at the input port and then, with the large-signal still incident, adds small signals, two (or more) per harmonic frequency per port, at controlled relative phases. This guarantees a well-conditioned set of measurements from which X-parameters can be unambiguously extracted, and reduces the measurements to the minimum number. The simulation is accomplished by an auto-configurable nonlinear frequency-domain simulation 'PHD block' component, compiled into Agilent ADS, based on the work of [1]~[3]. The automatically characterized and extracted X-para-meter data, that can include bias, power, and fundamental frequency as swept independent variables, is stored in an ADS-readable MDIF file for the simulation component. The ADS functionality automatically converts the measured datafile into a device-specific PHD block instance. The framework enforces additional physical constraints on the measured X-parameter representation of the component, including time-translation invariance and Volterra asymptotic behavior for low amplitude drive. A simplified representation of the NVNA and its interoperability with ADS is shown in [Fig. 1].

Ⅲ. X-parameters Versus 'Hot S22'

The simplest expression for X-parameters used in this work, is given by Eq. 1[1],[2]. Here we use a different notation and break up the contributions to the scattered and transmitted (pseudo) waves *Bpk*, at port *p* at the *k* th harmonic frequency, into three terms. The first term represents the large-signal response of the component to a single large-amplitude tone at a given fundamental frequency, assuming a perfect match at all ports at all harmonic frequencies. The second and third terms represent a linear non-analytic mapping of complex incident phasors at port index *q* and harmonic frequency index *l* into complex output phasors at port index *p* and harmonic frequency index *k*. The term *P* is the phase of the input large tone. The sum is over all ports and up to the number of harmonics measured. It is clear from (Eq. 1) that unlike linear S-parameters, X-parameters are nonlinear functions of the input signal power and map incident signals at specific frequencies to other frequencies. Another key feature of X-parameters, unlike linear S-parameters, is the appearance of terms proportional to the conjugate of the incident waves.

$$B_{pk} = X^{(F)}_{pk}(|A_{11}|)P^{k} + \sum_{q,l} X^{(S)}_{pk,ql}(|A_{11}|)P^{k-1} \cdot A_{ql} + \sum_{q,l} X^{(T)}_{pk,ql}(|A_{11}|)P^{k+l} \cdot A^{*}_{ql} \tag{1}$$

The term $X^{(s)}_{21,21}$ can be identified with a definition of 'Hot S22'[6]. In this sense, Hot S22 accounts for that part of the transmitted wave at port two (at the fundamental frequency) that is proportional to the incident complex phasor at port two(also at the fundamental frequency), evaluated while the amplifier is being driven with a large-amplitude signal at port one. An important benefit of the NVNA and the X-parameter extraction technique[4] is that together they provide an accurate, fast, and 'on-frequency' method of measuring Hot S22. However, Hot S22 is not sufficient to predict the phase dependence of B_{21}, the output wave at port 2 at the fundamental frequency, on A_{21}, even for small-amplitude A_{21}, the incident wave at port two at the fundamental frequency, under large-amplitude drive at port one (large A_{11}). This is demonstrated in [Fig. 2] for measured X-parameters of a GSM handset amplifier. Details are presented in [7]. Measured values of B_{21} are in excellent agreement with the predictions of Eq. 1 only when the $X^{(t)}_{21,21}$ term is added. The prediction from Hot S22 ($X^{(s)}_{21,21}$) alone is far from the data.



[Fig. 2] Measured complex amplitudes of fundamental responses at output port, B_{21} (small 'X's at end of radial solid lines), X-parameter predictions (points on elliptical shape) and Hot-S22 predictions (points on circle) for a commercial GSM amplifier. The output corresponds to large amplitude A_{11}, and fixed small amplitude A_{21} sampled at 11 phases between 0 and 360 degrees.

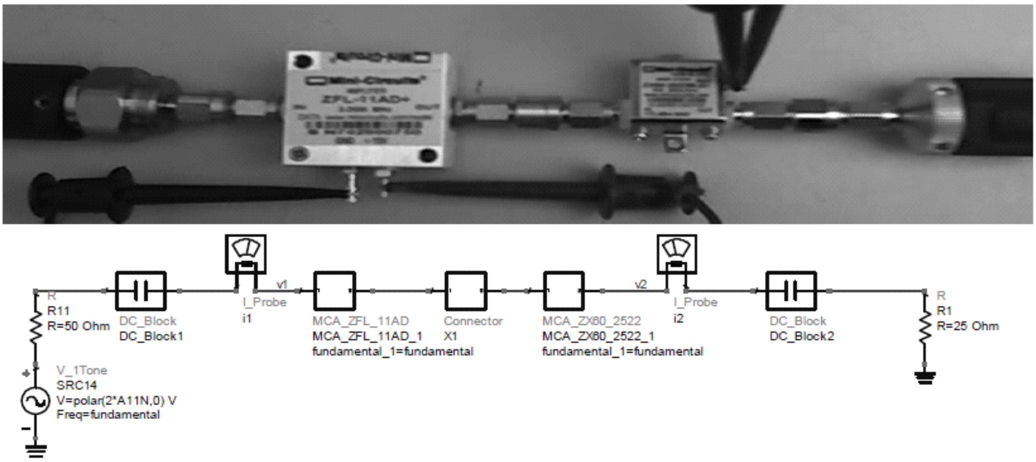
Ⅳ. X-parameter Design of Cascaded Nonlinear Amplifiers

It is not surprising, therefore, that it is important to include the $X^{(t)}_{pk,ql}$ terms to predict the behavior of cascaded nonlinear components under large drive. [Fig. 3] shows a design consisting of two cascaded amplifiers, each represented by NVNA-measured X-parameters encapsulated in a PHD simulation block.

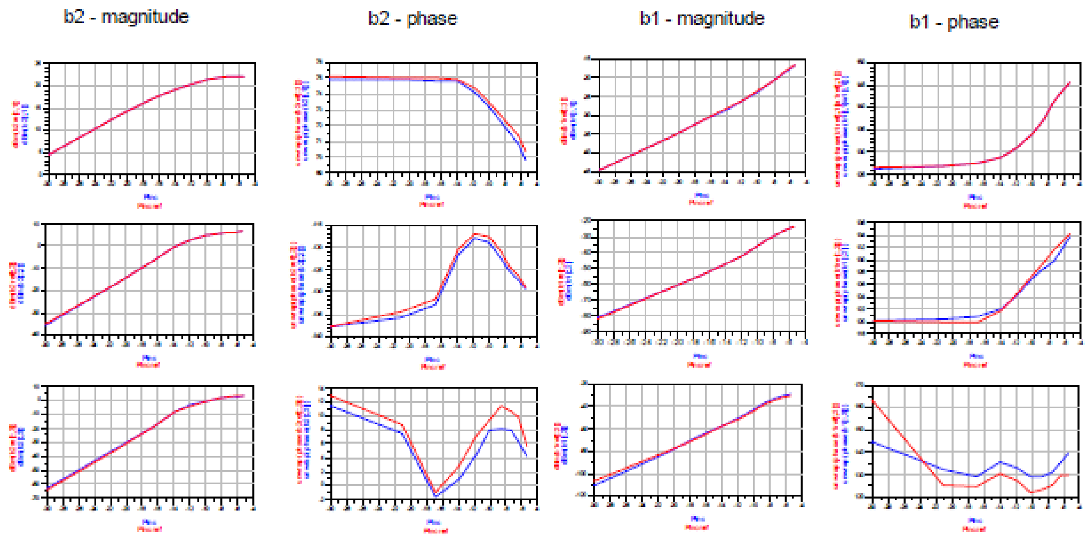
[Fig. 4] depicts independent NVNA measurements of the cascaded two-amp system, compared to the simulation of the cascaded amplifiers. This demonstrates the cascadability of nonlinear components using measured X-parameters up through three harmonics.

[Fig. 5] quantifies the importance of the $X^{(t)}_{pk,ql}$ terms (for which there are no S-parameter analogues) contributing to the output at port two at the fundamental frequency. This is the first time, to the authors' knowledge, that these specific contributions to a nonlinear cascade analysis has been published. It demonstrates the superiority of X-parameters to 'Hot S22', which only considers the power-dependence of a single term, $X^{(s)}_{21,21}$. Adding the term $X^{(s)}_{pk,ql}$, also relating purely fundamental frequency input-out relationships but not included by classic Hot S-parameter techniques, makes a large improvement, especially at high drive levels for A_{11}, where the relative phase of A_{21} compared to A_{11} becomes important to the scattered waves[1]. Adding harmonics improves the results still further. All desired X-parameters are automatically extracted by the application.

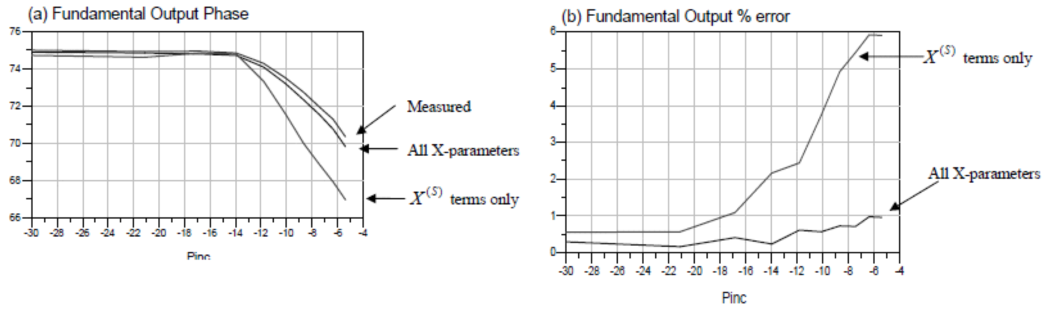
Using standard nonlinear analysis in ADS, the measured DUT X-parameters can be immediately used to reconstruct the time-domain waveforms (even under very large compression), estimate nonlinear figures of merit (FOM) such as IP3, ACPR, and EVM, and design multiple stage amplifiers or RF subsystems, and optimize system performance as a function of the DUT characteristics and design parameters.



[Fig. 3] Photograph of cascaded amplifier configuration, and ADS schematic with block implementations of X-parameter data from each specified amplifier.



[Fig. 4] ADS simulations (blue) of the transmitted (b2) and reflected (b1) waves, magnitude and phase, at the fundamental frequency (top row) and the second and third harmonics (rows 2 and 3, respectively) versus input power of the cascaded two-amplifier setup, based on measured X-parameters of each component. Independent NVNA measurements (red) of the measured cascaded system.



[Fig. 5] (a) Measured output phase of cascaded system (top trace); simulated output phase using all X-parameters through 3rd harmonic (middle trace); simulated output phase using no $X_{pk,ql}^{(t)}$ terms but all $X_{21,21}^{(s)}$ terms (bottom trace) versus input power. (b) Relative error of fundamental output of cascade, with just $X_{21,21}^{(s)}$ terms (top trace), and with all $X_{pk,ql}^{(t)}$ and $X_{21,21}^{(s)}$ terms (bottom trace) versus incident power.

Ⅴ. Conclusions

Predictable measurement-based large-signal design has been demonstrated with a unique set of inter-operable commercially available nonlinear technologies for measurement, simulation, and design of nonlinear components. The new NVNA instrument, automated

X-parameter measurements and extraction, and auto-configurable compiled PHD component in ADS, together enable design of nonlinear circuits entirely from fully calibrated nonlinear component data.

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