SECURING SUCCESSFUL FIRST-PASS COMPONENT DESIGN AND UNDERSTANDING X-PARAMETER NONLINEAR MEASUREMENTS

John J. Swanstrom, Application Engineer
Agilent Technologies
1400 Fountaingrove Parkway
(707) 577-3874; john_swanstrom@agilent.com

Abstract: This paper introduces significant advances in commercially available solutions for characterization, modeling, and design of nonlinear components and systems based on X-parameter[1] technology. X-parameters unify S-parameters, load-pull, and modern waveform measurements for more complete nonlinear characterizations and predictive nonlinear design of RF and microwave components and systems. Benefits never thought possible are being realized today by practicing engineers.

[1]X-parameters are a trademark of Agilent Technologies.

1. INTRODUCTION

At one time, linear systems and components were designed using a patchwork of instrumentation and measurements. This approach was quickly replaced by Scattering parameters (S-parameters), which unified the multiple instruments and measurements and enabled just one instrument, the network analyzer, to make measurements like gain, isolation and match with a single connection. For more than 40 years, S-parameters have stood as one of the most important of all the foundations of microwave theory and techniques. They are related to familiar measurements such as S_{11} input match, S_{22} output match, S_{21} gain/loss, and S_{12} isolation, and can be easily imported into electronic simulation tools. Today, S-parameters are commonly used to analyze and model the linear behavior of RF and microwave components. Current industry trends toward increasing energy efficiency, higher output power and longer battery life are forcing many linear devices to operate in a nonlinear fashion. Measuring this behavior requires a solution that is much more deterministic in nature.

2. THE DESIGN PROBLEM

While extremely useful and powerful, S-parameters are only defined for small-signal linear systems. With the communications revolution forcing active components like power amplifiers (PAs) into more and more strongly nonlinear regimes of operation, engineers are now forced to use a new set of patchwork solutions for measuring a component's nonlinear attributes. Essentially, they make linear assumptions by taking S-parameters and applying nonlinear figures of merit (e.g., ACPR and gain compression). Relying on this incomplete set of information means that the engineer has to perform extensive and costly empirical-based iteration of their designs, adding substantial time and cost to the design process. To quickly, accurately and more deterministically design nonlinear components at high frequencies, today's engineers require the ability to properly measure nonlinear behavior, as well as a unifying model (similar to an S-parameter, but for nonlinear components) that can take this behavioral information into simulation and design.

3. RESULTS

By doing for nonlinear components and systems what S-parameters do for their linear counterparts, X-parameters offer engineers an answer to this dilemma. X-parameters represent a new category of nonlinear network parameters for deterministic, high-frequency design and are used for characterizing the amplitudes and relative phase of the nonlinear behavior of components. Unlike S-parameters, they are applicable to both large-signal and small-signal conditions, and can be used for linear and nonlinear components. They correctly characterize impedance mismatches and frequency mixing behavior to allow accurate simulation of cascaded nonlinear X-parameter blocks (e.g., amplifiers and mixers), in design.

In contrast to S-parameters, X-parameters represent and analyze the nonlinear behavior of RF/MW components in a much more robust and complete manner. As the logical, mathematical extension of S-parameters under large-signal operating conditions, they are driven into saturation (the real-world operating environment for many components) and then measured under these conditions. When making this measurement, no knowledge is used or required concerning the internal circuitry of the device under test (DUT). Rather, the measurement is a stimulus and response model of the voltage waves (Figure 1). In other words, the absolute amplitude and cross frequency relative phase of the fundamental, and the generated distortion products, are accurately measured and represented by X-parameters. Corresponding X-parameter-based behavioral models are created from this information (Figure 2) and can be used with calibrated measurement tools to derive different figures of merit (e.g., ACPR, compression and EVM). These fast, accurate models can take into account a range of different variables including source and load impedance, among other things.

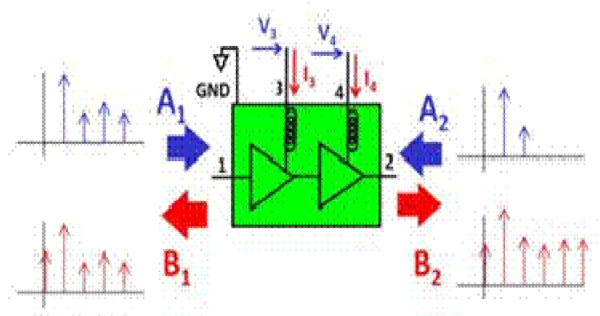

Figure 1. *The X-parameter model for the multi-stage amplifier in this example is formulated in the frequency domain and maps incident waves (A) to scattered waves (B). Because the complete knowledge of magnitude and phase of incident and scattered waves at all harmonics is exactly equivalent to complete knowledge of the time-domain waveform, the full nonlinear input-output characteristics of the device are captured.*

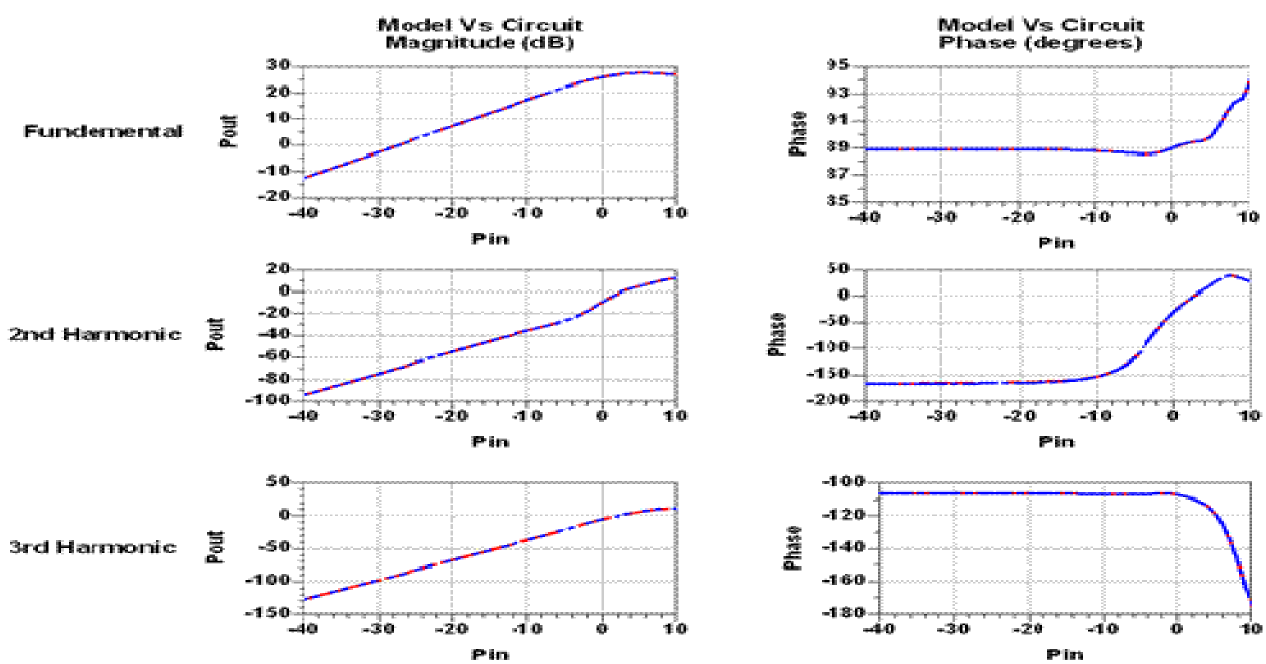

Figure 2. *Comparison of predicted performance from simulation using X-parameters (blue traces), versus the actual measured behavior of the circuit-level power amplifier (red traces). As is evident, the X-parameter simulation accurately correlates with the actual circuit.*

3.1. Generating X-Parameters

X-parameters can be obtained in one of two ways: generated from a circuit-level design in Agilent Technologies' Advanced Design System (ADS) software or measured using the Nonlinear Vector Network Analyzer (NVNA) firmware running inside the Agilent Technologies' PNA-X network analyzer (Figure 3).

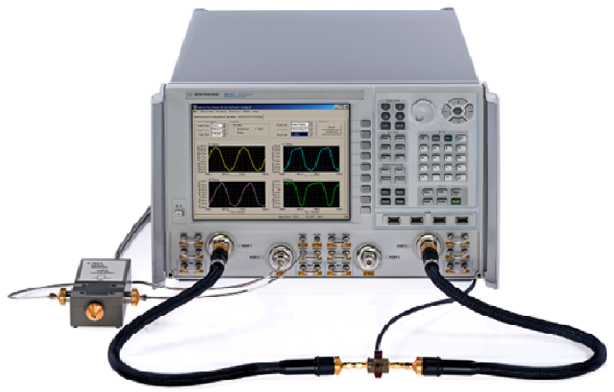

***Figure 3**. Agilent's NVNA firmware, for use with the PNA-X network analyzer, establishes a new industry standard in RF/MW nonlinear network analysis from 10 MHz to 50 GHz. It allows the engineer to deterministically measure X-parameters.*

To generate the X-parameters from a circuit-level schematic, first create the schematic in ADS. Once the schematic is complete, information regarding frequency, bias, temperature, and other important parameters is entered into the X-Parameter Generator. This tool takes the circuit-level design and computes the X-parameters for a component or module that can be used in an ADS, harmonic balance or circuit envelope simulation. The X-parameter Generator is very flexible and can generate X-parameter models of nonlinear, multi-port components with multi-tone stimulus, as well as simulation under load-pull conditions.

Obtaining quick and accurate X-parameters through measurement requires the use of Agilent's NVNA (Figure 3). It measures the X-parameters of the DUT, which can then be imported into the ADS simulator or displayed like S-parameters. To measure the X-parameters the NVNA uses it's two internal RF sources to drive the DUT with a large signal tone to set the large signal operating point of the device and at the same time applies a small signal tone at the appropriate frequencies and phases. Careful control of the phase and amplitude of these signals is therefore critical (Figure 4). Measuring the amplitudes and phases of the scattered waves under these conditions allows for the identification of X-parameters. These parameters provide the engineer with information on such things as device gain and match, while the device is operating in either a linear or nonlinear state.

3.2. Nonlinear Calibration Procedure

While calibrating a nonlinear measurement system may seem like it could be a complicated process and procedure, calibration is actually quite simple and straightforward. The vector network analyzer requires a vector calibration standard such as an ECal module or mechanical calibration standards to remove the systematic errors associate with vector corrected measurements, a power meter or USB power sensor to calibrate the signal power levels incident on the device under test (DUT), and a phase reference to provide a cross-frequency phase reference for the harmonic signals. The NVNA provides a guided calibration sequence that prompts the user to connect the standards, and the firmware performs the appropriate measurements and calculations to provide calibrated nonlinear measurements that are traceable to NIST.

***Figure 4:** Calibration standards used for calibrating a NVNA, showing (left to right) a vector calibration standard (ECal module), USB power sensor, and phase reference which are used to analytically remove the systematic errors from the measurements.*

4. DISCUSSION

The accurate and robust nature of X-parameters makes them extremely useful for engineers trying to better understand the nonlinear behavior of their active components. Whether created or measured, these X-parameters can be easily imported into ADS and then dropped into a component or system to start the design process or for use with simulation. There are other key features and benefits of X-parameters. X-parameters are extensible beyond 50 Ω. While network analyzers are inherently 50 Ω devices, the extensibility of X-parameters enables components to be measured beyond this point (e.g., a PA at 3 Ω). This can be done by either placing a matching circuit between the network analyzer and the DUT, or by employing a load pull tuner. In addition, since the X-Parameter Generator in ADS has no limits on the number of ports, power or frequency it can handle, it is able to deal with complicated designs involving multiple ports (e.g., 3-port devices such as mixers), tones and biases, as well as arbitrary topology. In the future, such capabilities will also be available in the NVNA to make the physical measurements of X-parameters.

For high power applications, X-parameters are currently targeted at active devices, like power amplifiers (PA), that commonly exhibit strong nonlinear behavior. The NVNA can make high power X-parameter measurements (e.g., 10, 100 and 250 watt devices), even if the base network analyzer configuration can only handle 1 watt. The flexibility of Agilent's PNA-X hardware has enabled measurements to be made to 100, and even 250 watts.

5. SUMMARY OF RESULTS

With active components continuing to be driven into nonlinear operation, the need for fast and accurate measurement of that nonlinear behavior becomes all the more urgent. As a logical extension of S-parameters to include nonlinear effects, accurate and robust X-parameters represent the ideal solution to this dilemma. Whether created from measurement or ADS simulation, they offer speed and convenience analogous to the well-known linear S-parameters. Resulting X-parameter-based behavioral models can be quickly and easily dropped into simulation and used to deterministically design the most robust components and systems in the shortest amount of time and with the highest degree of accuracy.

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