

Solutions for

Characterizing Complex and Multi-Stage Circuits

Using Arbitrary Load Impedance X-Parameters to Optimize Non-50-ohm Measurements

Application Note



Overview

Large signal models can provide an ideal form for nonlinear device characterization. Such models are especially beneficial in the design of complex or multi-stage circuits because they can enable analysis of performance for varying drive and impedance conditions. Much work has been devoted to large signal model development at microwave frequencies. While the models can be accurate over certain regions of the device operation, they may fail in other areas. Since they are typically extrapolated from DC and small-signal measurements, verification under actual large-signal operation is generally required with mixed results. In many cases of practical interest, the device is used over a wider range of voltage and current than can even be characterized under DC and linear Scattering parameter (S-parameter) conditions, which can lead to errors.

X-parameters* are a measurement of a device under actual operating conditions which include large-signal operation. The vector load impedance dependency can now be included with S-parameters for non-50 ohm devices using traditional load pull tuners.

Problem

Engineers charged with designing today's complex and multi-stage circuits are faced with a key question: what matching circuit do I need to apply to get the maximum efficiency or power output from my design? Load pull offers a means of answering this question. Load-pull tuners were designed to aide in this process. Used with a power meter, they allow the engineer to change their device's load impedance and map the contours of the efficiency curves and power-added-efficiency (PAE) on a Smith Chart. The resulting information allows the engineer to determine the impedance needed to achieve maximum power and PAE of a single stage device.

The problem with traditional load pull data is that it is really a one-port, scalar measurement often done at the fundamental frequency only. It does not provide phase information and, if harmonic interactions are included, does not include the cross-frequency phases of the harmonics. Consequently, it does not provide enough information to reconstruct the terminal waveforms of the device when they are highly distorted under large-signal conditions. While the traditional load-pull measurement works well for simple amplifiers, the same cannot be said of complex or multi-stage circuits. It simply is not sufficient to be used independently in the simulator as a component model.

Solution

X-parameters represent a new category of nonlinear network parameters for deterministic, high-frequency design and are used to characterize both a component's linear and nonlinear behavior. They are measured using a network analyzer with the addition of a phase reference and nonlinear firmware option. For devices which are roughly 50 ohms (say 25 to 100), X-parameters can extract the load dependent behavior of the device without the need for a load-pull tuner. When combined with a load-pull tuner, X-parameters provide a simple and direct way to get non-50 ohm load-dependent device behavior included in a large signal model for analysis of complex or multi-stage circuits. This nonlinear data can be loaded directly into the Agilent Advanced Design System (ADS) simulator to create an X-parameter component and used immediately for design and analysis of complex components and modules, including power amplifier (PA) circuits. The load-dependent X-parameters enable full waveforms to be predicted, calibrated to the device terminals—even under high degrees of compression—over all impedance environments for fundamental and harmonic spectra.

Measurement Theory

Why do X-parameters have the ability to treat certain signals as large signals and others as small signals? To answer this question, consider that the large-signal steady-state behavior of a RF or microwave component is completely determined by its nonlinear constitutive relations, $B(A)$, which specify the output, or scattered B-waves as complex-valued nonlinear functions of the complex-valued incident A-waves. For practical purposes, the DUT $B(A)$ constitutive relations can be simplified and in the extreme case, leads to S-parameters which result from approximating the entire dependence on every B-wave as linear in each spectral component of each incident A-wave. At the other extreme (no approximation), each B-wave depends nonlinearly on each component of every incident

A-wave. In practice, only one or two levels beyond S-parameters are required to provide an excellent approximation to the nonlinear $B(A)$ relations, even under very strong nonlinear conditions—a concept referred to as spectral linearization.

X-parameters are based on the use of spectral linearization around a large-signal operating point. They can therefore provide very accurate correlation for devices around 50 ohms or when used with a matching circuit (non-50 ohm). They can also capture behavior for devices far from 50 ohm when not using a matching circuit, although some degradation results. Trade-offs between speed/simplicity versus accuracy can easily be accomplished by treating the load mismatch signal as a small signal or a large signal with the resulting arbitrary load dependency into the structure and measurement, the benefit of which is very accurate correlation at any impedance.

Making Load-Pull Measurements

Generally speaking, X-parameters can be obtained in one of two ways: generated from a circuit-level design in Agilent Technologies' ADS software or measured using the Nonlinear Vector Network Analyzer (NVNA) software running inside the Agilent Technologies' PNA-X network analyzer (Figure 1).

For complex and multi-stage circuits operated under highly mismatched conditions, load-pull X-parameters can be measured over the entire range of load conditions of interest using a fundamental load tuner together with the NVNA. The setup for this measurement is shown in Figure 2. Resulting load-dependent X-parameters are accurate over the entire region of measured load conditions.

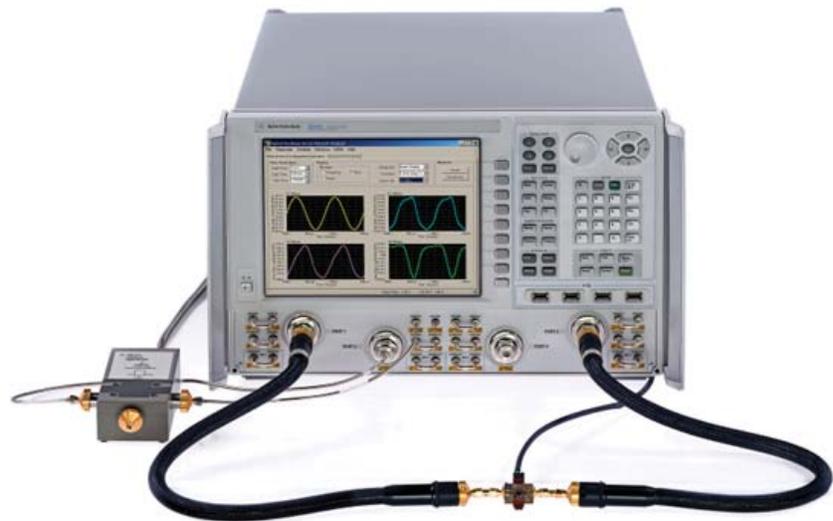


FIGURE 1: Agilent's NVNA software, for use with the PNA-X network analyzer, establishes a new industry standard in RF/Microwave nonlinear network analysis from 10 MHz to 50 GHz. It allows the engineer to deterministically measure X-parameters.

The measurement can include a complete sweep plan with the device operating condition variables (e.g., impedance, RF power, dc bias, and frequency) that can extend the applicability of the X-parameters over a much wider range of validity (e.g., over the range of actual applications for many high-power and multi-stage PA designs). The process has two steps:

1. The load-pull system (a fundamental load tuner with the NVNA) measures the X-parameters at all specified impedance settings (e.g., over the entire Smith Chart), along with the other variables specified in the sweep plan, and saves the resulting data in a single file. Corrections for accurate re-gridding and calibrating out the uncontrolled harmonic impedances are then applied.
2. The data is dropped into Agilent's ADS, creating a component which can be directly used in a circuit schematic as a nonlinear device. Analysis can immediately follow. Note that because the component is based on measurement at the actual operating conditions of the device, it is extremely accurate and can be used in nonlinear analysis with great confidence.

This process has a number of critical benefits. First and foremost, it provides the simplicity of using load-pull and NVNA data directly for simple PA design, but can also be used to analyze complex circuits requiring large-signal models. Because it applies equally to modeling an amplifier section, it is not limited to characterizing a single device. Moreover, it is independent of the device technology. In addition, the process provides a much more automated and repeatable means of extracting full load-dependent X-parameters at multiple harmonics than extracting a standard "compact" transistor model.

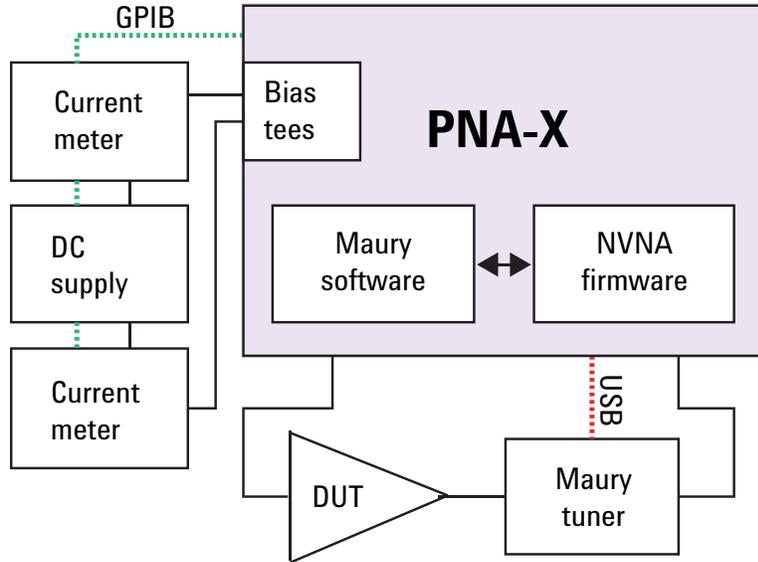


FIGURE 2: Shown here is the measurement setup for load pull with X-parameters.

Example: 1-Watt HFET

To validate the load-pull X-parameter measurement process previously outlined, consider the example of a 1-watt HFET (the FP2189 from WJ Communication) mounted on a connectorized PC board. It was measured using the Maury tuner model MT982EU30 and Agilent PNA-X model N5242A with NVNA and X-parameter options. All measurements were de-embedded up to the package pins. The results of a standard

load-pull measurement of delivered power and efficiency were compared with the results of a load-pull simulation in ADS using the X-parameter component with measured load-dependent X-parameters (Figure 3). Both the simulated and the independent measured results are in excellent agreement.

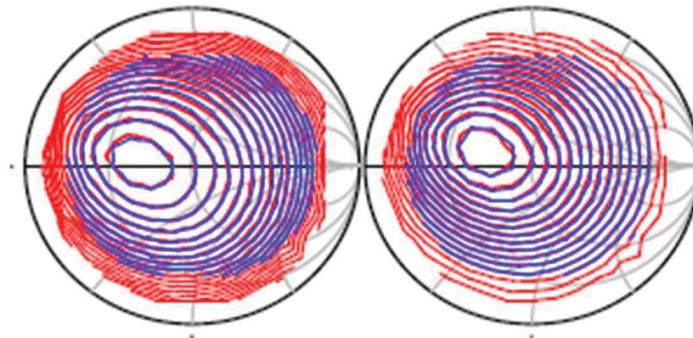


FIGURE 3: Comparison of simulated (blue) and independent measured (red) delivered power contours (left) and efficiency contours (right).

Example 2: Capturing the DUT's Harmonic Behavior

Time-domain load pull combines active or passive systems with receivers capable of measuring waveforms in the time domain or multi-harmonic spectra (magnitude and phase) in the frequency domain. It provides a complete description of the power and complex load-dependence of an active device under large-signal steady-state conditions.

Because X-parameters can capture the harmonic behavior of the device, in addition to its fundamental RF and DC behavior, they provide a fast and efficient way to capture dependence on harmonic load and upstream source harmonics without the need for a much longer full harmonic load-pull measurement. Since magnitude and phase of harmonics are captured, the full time-domain waveforms are available. To validate this, independent measurements were first taken and then measured load conditions were presented at the fundamental and harmonics to the X-parameter component in simulation. As shown in Figure 4, both the simulated and the independent measured results are in excellent agreement.

Summary of Results

While traditional load-pull measurements can work well for determining the optimal load impedance for simple amplifiers, they do not provide enough information to characterize complex or multi-stage circuits under large-scale conditions. When combined with load pull, X-parameters provide an efficient way to quickly get load-dependent device behavior included in a large signal model for analysis of complex PA circuits.

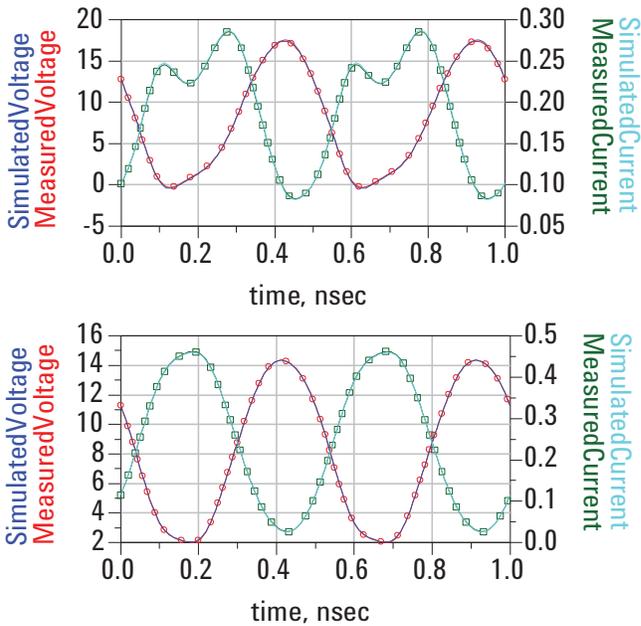


FIGURE 4: Comparison of simulated and independent measured time domain waveforms at fundamental gamma of $0.383+j*0.31$ (above) and $-0.272+j*0.048$ (below).

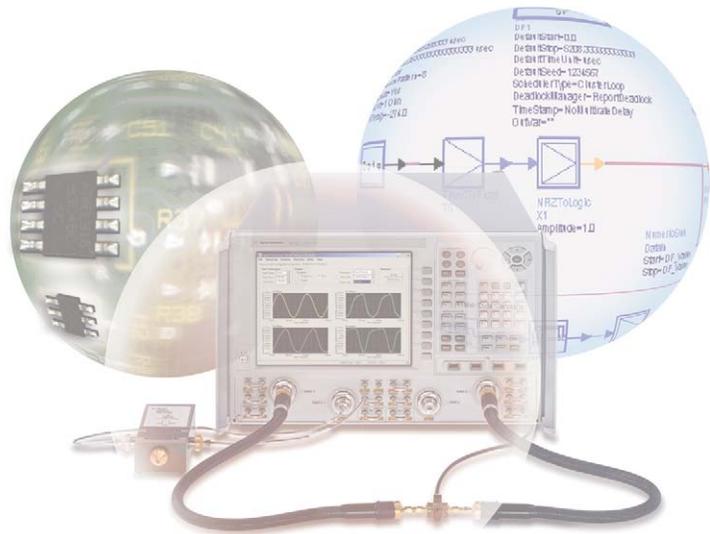


The Power of X

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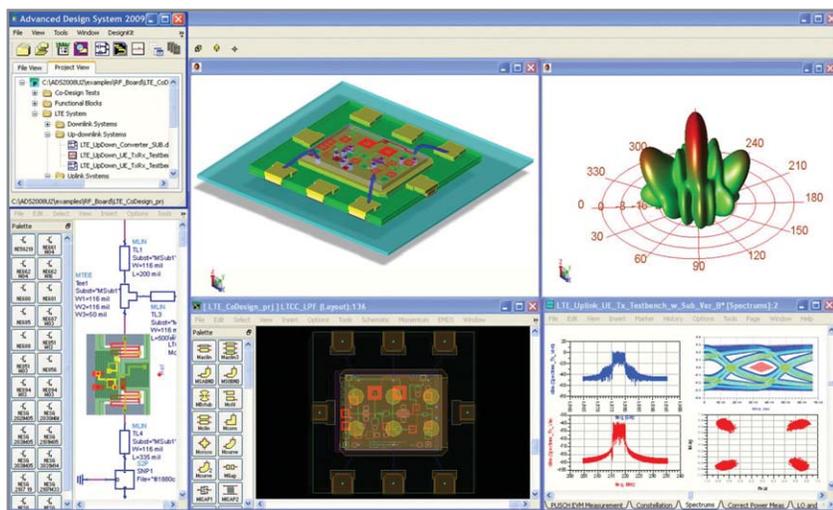


Related Applications

- Semiconductor process design
- Semiconductor IC design and validation of active components
- Base station PA design and validation
- Military active component design and validation

Related Agilent Products

- W2305 X-Parameter Generator
- W2200 ADS Core
- Nonlinear Vector Network Analyzer



W2200 ADS Core

* X-parameters is a registered trademark of Agilent Technologies. The X-parameter format and underlying equations are open and documented. For more information, visit <http://www.agilent.com/find/eesof-x-parameters-info>

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