Load Pull + NVNA = Enhanced X-Parameters for PA Designs with High Mismatch and Technology-Independent Large-Signal Device Models

Gary Simpson[1], Jason Horn[2], Dan Gunyan[2], and David E. Root[2]

[1] Maury Microwave Corporation, Ontario, CA, 91764, USA
[2] Agilent Technologies, Santa Rosa, CA, 95405, USA

Abstract — *X-parameters [1-4] are the mathematically correct supersets of S-parameters valid for nonlinear (and linear) components under large-signal (and small-signal) conditions. This work presents an automated application combining a Nonlinear Vector Network Analyzer (NVNA) instrument with automated load-pull measurements that extends the measurement and extraction of X-parameters over the entire Smith Chart. The augmented X-parameter data include magnitude and phase as nonlinear functions of power, bias, and load, at each harmonic generated by the device and measured by the NVNA. The X-parameters can be immediately used in a nonlinear simulator for complex microwave circuit analysis and design. This capability extends the applicability of measurement-based X-parameters to highly mismatched environments, such as high-power and multi-stage amplifiers, and power transistors designed to work far from 50 ohms. It provides a powerful and general technology-independent alternative, with improved accuracy and speed, to traditional large-signal device models which are typically slow to develop and typically extrapolate large-signal operation from small-signal and DC measurements.*

Index Terms — *microwave measurements, design automation, modeling, nonlinear circuits, power amplifiers, simulation, X-parameters.*

Introduction

Device characterization is required for power amplifier design, and the ideal form of the device data is a large signal model. With a model, the performance can be analyzed for varying drive and impedance conditions, so complex or multi-stage circuits can be designed.

Much work has been devoted to large signal model development at microwave frequencies, and improvements have been made in recent years. But though these analytical 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. 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 S-parameter conditions. Load pull is a measurement of a device under actual large signal operation. It may include measuring device performance vs. impedance, drive power, bias, temperature, or other factors. Since it is a direct device measurement, the data can be used with confidence over the conditions of the measurement.

Load pull data can be used directly for power amplifier design, by determining the impedance terminations required for device operation. A linear simulator can then be used to design the input and output matching networks. But this approach generally works well only for simple amplifiers, not for more complex or multi-stage circuits. This method has been widely used when large signal models are not available or not trustworthy. However, conventional load-pull data typically does not provide the magnitudes and all the cross-frequency phases of the harmonics, and therefore does not provide enough information to reconstruct the terminal waveforms of the device when they are highly distorted under large-signal conditions. It is therefore not sufficient to be used independently in the simulator as a device model.

A second way that load pull data is used for power amplifier design is to validate large signal models. The load pull data is measured during actual device operation, so is used as reference data. The large signal model is compared to the load pull data, and may be adjusted as needed to get accurate analysis in the region of interest. At that point, the large signal model can be used for more complex circuit analysis.

An alternate way of formulating a large signal model is to use a measurement-based behavioral approach, as with the PHD model. This is based on measurements of X-parameters, which are a superset of S-parameters for nonlinear components, and are measured using an NVNA (Non-linear Vector Network Analyzer). S-parameters measure the complex magnitude and phase relationship between small signals at the same frequency at different ports, but don't account for additional spectral components generated by the DUT under large-signals, or the interaction among different frequency signals incident on a device whose state is time-varying due to large-signal stimuli. X-parameters include harmonics and intermodulation frequency components, and also the relationships between all those frequencies for a given drive amplitude and frequency, enabling the complete waveforms – including those corresponding to strongly compressed conditions - to be measured at the device terminals. However, a stand-alone NVNA does not stimulate the device over a wide range of impedance states at which the X-parameters are measured. Therefore, the simplest 1-tone PHD model [1,4] is extracted only over a limited impedance range around the characteristic impedance of the NVNA, typically 50 ohms, or around an arbitrary but fixed impedance presented by an impedance transformer or matching structure used to present a different impedance environment to the device output. Most high-power transistors and amplifiers have optimal performance far from 50 ohms. It is therefore necessary to acquire X-parameters over large areas of the Smith Chart in order for the resulting model to remain valid over the corresponding range of loads it might be expected to encounter in applications. The limitation is not with X-parameters or the PHD framework for simulating with X-parameters [3], but rather with providing a simple, fast, automated measurement system and application to acquire the X-parameters over the entire complex load-domain of interest.

Load Pull with X-Parameters

This paper introduces load pull with NVNA measurements of X-parameters that produce data that can be used directly by the PHD model over a wide impedance range. The operator of the combined load pull NVNA system will select an impedance range of interest, possibly over the entire Smith chart. The PHD model can then be used as a circuit element in a non-linear analysis with great confidence, since it is based on measurement at the actual operating conditions of the device.

The load pull X-parameter measurement can include a complete sweep plan. Stimulus variables can include impedance, power drive, bias, and frequency, for example. This can extend the applicability of the PHD model over a much wider range of validity – over the range of actual applications for many high-power and multi-stage PA designs.

The process has three steps:

1) The load pull system measures the X-parameters at each impedance setting, like a standard load pull, with X-parameters added to the measurement data set. When the measurements are complete at all the impedances, the measured X-parameters are saved into a single file.

2) An enhanced design kit available for use in the ADS non-linear simulator then reads the file saved by the load pull - NVNA system and creates a PHD component associated with the file. This is a very quick step.

3) This component can then be dragged and dropped directly into a circuit schematic as a non-linear device, and analysis can start immediately.

This process is a huge simplification over past practice. It provides the simplicity of using load pull and NVNA data directly for simple power amplifier design, but with the ability to analyze complex circuits that require a large signal model. It also is not limited to characterizing a single device, but applies equally to modeling an amplifier section. The process is also independent of the device technology. Extracting full load-dependent X-parameters at multiple harmonics is much more automated and repeatable than extracting a standard "compact" transistor model, which may have more than 100 parameters that have to be optimized to give overall fits. It is thus ideal for new technologies and new amplifier realizations before any detailed physics-based compact models or accurate circuit-level models are available.

System Configuration

Although the measurement system is capable of taking much more complex measurements than a classic load-pull system, in many ways the setup is actually much simpler. A typical scalar load-pull system may involve a computer running the controlling software, multiple power meters, a spectrum analyzer, DC supplies and meters, one or more sources, and one or more tuners along with attenuators, bias tees, couplers, etc. Utilizing Agilent's latest premier network analyzer, the PNA-X, many of these separate components and instruments are no longer necessary because they are already contained inside the box. This results in a simpler setup with fewer components, an easier use model, and faster measurements.

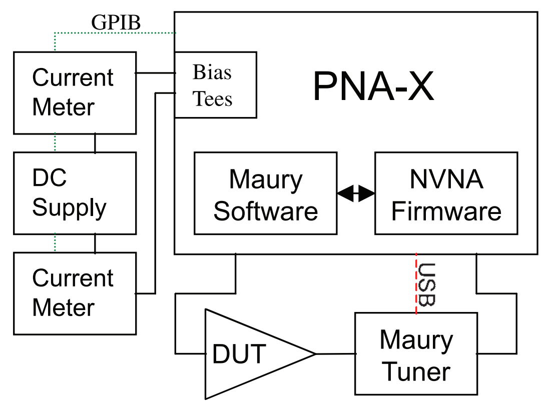

Figure 1. Measurement setup for load pull with X-parameters

The central piece of the measurement setup is the PNA-X with NVNA and X-parameter options. In addition to serving as a time domain measurement system with 26 GHz of bandwidth, the Maury ATS software can run directly on the analyzer for maximum interoperability and speed, eliminating the need for a dedicated measurement computer. The necessary couplers, bias tees, and RF sources are also already included in the box, so connecting the system is relatively simple as seen in figure 1. The USB-controlled tuner plugs directly into the analyzer, and the DC instruments are controlled through the built-in GPIB interface. Since both the NVNA firmware and ATS software have built-in support for external instrument control through GPIB, bias sweeps are easy to set up and measurement synchronization is automatically handled.

The user interface is primarily handled through Maury's ATS software, with the NVNA firmware used for calibration and made available for advanced settings (configuring internal switches and attenuators, utilizing advanced features of the PNA-X such as pulse modulation or triggering, etc.). Mea-

2900 Inland Empire Blvd. • Ontario, California 91764-4804
Tel: 909-987-4715 • Fax: 909-987-1112 • http://www.maurymw.com

surement configuration through the UI is similar to standard load-pull configuration, but using a simpler block diagram with the NVNA replacing several typical instruments. The measurement parameter "X-Params" is available when the NVNA is included in the setup. When it is not selected, time-domain load-pull (load dependent waveforms) measurements are taken. When selected, the X-parameters of the DUT are also measured as a function of load and any swept bias conditions. The resulting X-parameters are written to a single file at the end of the measurement that is immediately ready to be imported into ADS and used in simulation and design.

Simulation

The PHD Design Kit for ADS provides a framework for simulation using measured data. X-parameters measured on the NVNA can be directly imported through the design kit and immediately used for large signal simulation and design. The design kit was updated to support load-dependent X-parameters measured with the system described above. The use model is exactly the same as that of fixed-impedance X-parameters, and consists of copying the MDIF file containing the measured X-parameters into the ADS Project in which it will be used and using the "PHD" menu to create a component that is linked to that file. The entire process typically takes less than one minute, and the component can be immediately used in the Harmonic Balance or Envelope simulators, as shown in figure 2. Full large-signal behavior, including magnitude and phase of harmonics, are captured in the X-parameters and accurately predicted by the component.

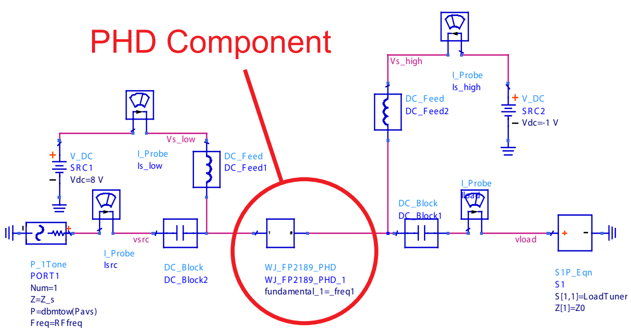

Figure 2. PHD Component linked to a file of measured X-parameters in an ADS schematic.

Results

The measured data was taken using the Maury tuner model MT982EU30, and the Agilent PNA-X, model N5242A, with the NVNA and X-parameter options, as shown in figure 1. The DUT measured is a packaged FP2189 1 Watt HFET from WJ Communications (now a part of TriQuint Semiconductor) mounted on a connectorized PC board. All measurements were deembedded up to the package pins.

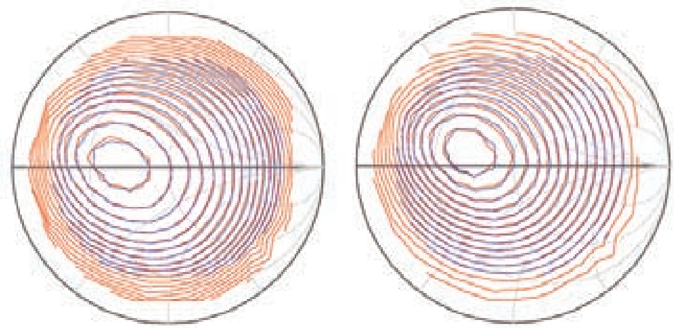

Figure 3. Comparison of simulated (blue) and independent measured (red) delivered power contours (left) and efficiency contours (right)

The first basic validation was done by comparing a standard load-pull measurement of delivered power and efficiency with the results of a load-pull simulation in ADS using the PHD component with measured load-dependent X-parameters. As figure 3 illustrates, the agreement between simulated and the independent measured results is excellent.

In addition to fundamental RF and DC behavior, the X-parameters also capture the harmonic behavior of the device. Since magnitude and phase of harmonics are captured, the full time-domain waveforms are available, as shown in figure 4.

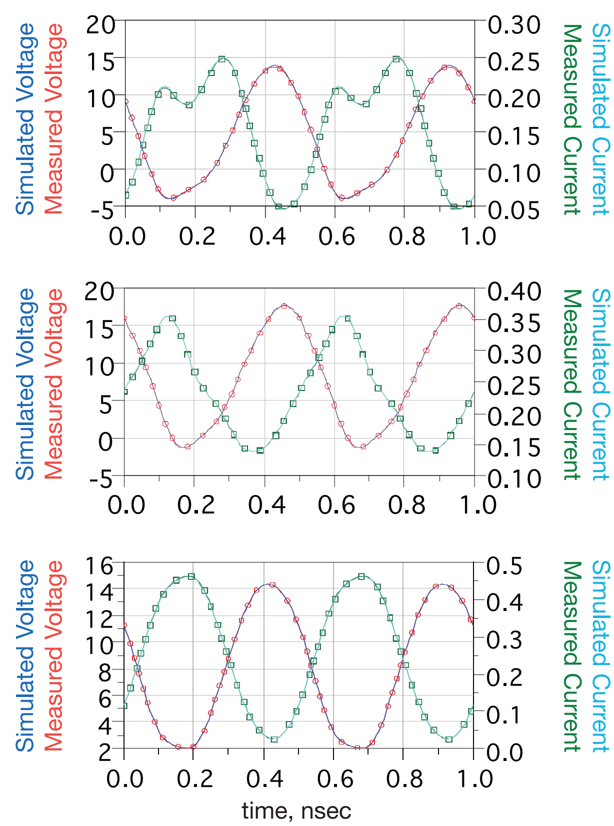

Figure 4. Comparison of simulated and independent measured time domain waveforms at fundamental gamma of 0.383+j*0.31 (top), 0.387-j*0.466 (middle), and -0.272+j*0.048 (bottom).

Again, the agreement between simulation and independent measured results is excellent. The comparison was done by first taking the independent measurements, then presenting the measured load conditions at the fundamental and harmonics to the PHD component in simulation.

The same harmonic load conditions were necessary for a valid comparison because the PHD component uses X-parameters to account for harmonic mismatch. This is an important note, because in addition to providing an automated framework for using nonlinear measured data in simulation, PHD and X-parameters provide an efficient way to capture dependence on harmonic load and upstream source harmonics, as shown in figure 5. Although X-parameters are not a complete replacement for harmonic load-pull in all cases, we anticipate that, for many devices, they will provide sufficient information to use in design without the need for a much longer full harmonic load-pull measurement.

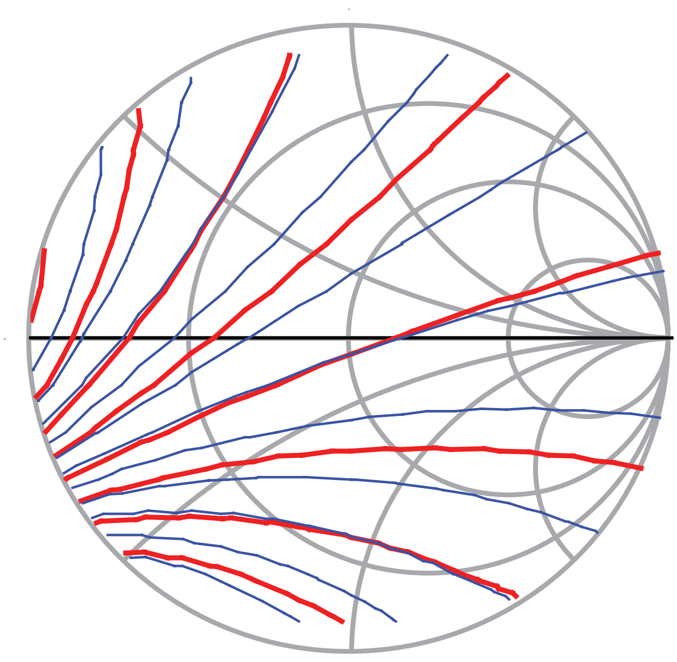

Figure 5. PAE (red) and Delivered Power (blue) contours vs. second harmonic load

Conclusion

Load pull with X-parameters together with the PHD framework provides a simple and direct way to get a large signal model for analysis of complex power amplifier circuits. The load pull measurement creates an X-parameter file which can be loaded directly into the non-linear simulator to use as the PHD component. The data can then be used immediately for analysis of complex power amplifier 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.

Acknowledgement

The authors wish to acknowledge the assistance and support of the Agilent management.

References

[1] J. Verspecht and D. E. Root, "Poly-Harmonic Distortion Modeling," in IEEE Microwave Theory and Techniques Microwave Magazine, June, 2006.

[2] J. Verspecht, D. Gunyan, J. Horn, J. Xu, A. Cognata, and D.E. Root, "Multi-tone, Multi-Port, and Dynamic Memory Enhancements to PHD Nonlinear Behavioral Models from Large-Signal Measurements and Simulations," 2007 IEEE MTT-S Int. Microwave Symp. Dig., Honolulu, HI, USA, June 2007.

[3] J. Horn, D. Gunyan , L. Betts, C. Gillease, J. Verspecht, and D. E. Root, "Measurement-Based Large-Signal Simulation of Active Components from Automated Nonlinear Vector Network Analyzer Data via X-Parameters," in 2008 IEEE COMCAS Conference, Tel Aviv, Israel, March, 2008

[4] D. E. Root, J. Verspecht, D. Sharrit, J. Wood, and A. Cognata, "Broad-Band, Poly-Harmonic Distortion (PHD) Behavioral Models from Fast Automated Simulations and Large-Signal Vectorial Network Measurements," IEEE Transactions on Microwave Theory and Techniques Vol. 53. No. 11, November, 2005 pp. 3656-3664.

Copyright Notice

2900 Inland Empire Blvd. • Ontario, California 91764-4804
Tel: 909-987-4715 • Fax: 909-987-1112 • http://www.maurymw.com