Synchronized Source/Load-Pull Analysis and Communication System Measurements for Powerful PA Design

This article describes how load-pull data files with an independent swept parameter such as power can be used directly in NI AWR software, specifically Microwave Office circuit design software.

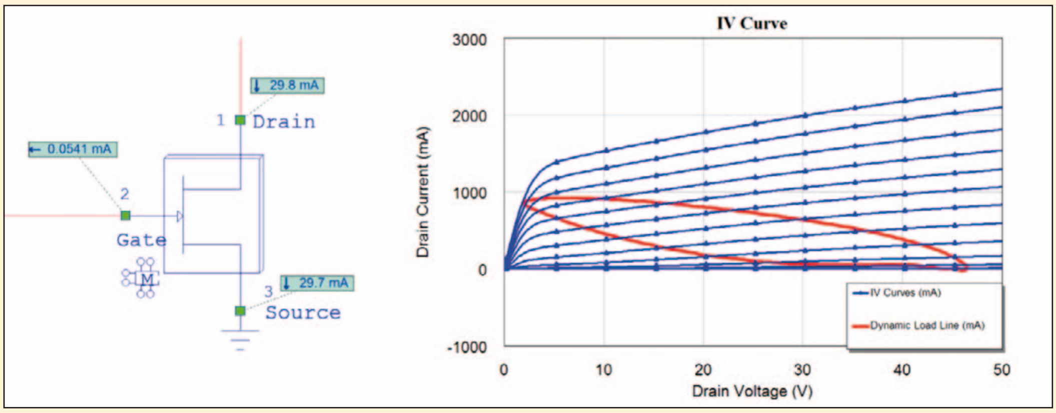

Figure 1: 10 W at P3 dB and 28 V drain voltage operation, class B behavior with dynamic load line shown

The design of a Class J PA is used as an example to show how the load-pull data can be used to complement traditional, theoretical Class J analyses and streamline the design flow.

Overview

A rich set of load-pull data provides power amplifier (PA) designers with the means to investigate the optimum capability of a communication device in relation to design goals and performance targets.

To fully benefit from this information, designers need an intuitive method for working with complex swept load-pull data sets. These data sets can include multiple fundamental frequencies, nested harmonic load pull, and/or nested source and load pull. As such, PA performance can easily be understood across multiple operating conditions. Measurements can include available output power, gain, efficiency, intermodulation distortion levels, or, essentially, any other performance metric that can be measured on a modern load-pull system. The measurements can be readily de-embedded to the current generator reference plane of the device, which is a critical consideration for any designer moving beyond the traditional reduced conduction angle classes of operation.

Background

Load-pull contours are acquired by sweeping the impedance presented to a device, measuring performance, and plotting the resultant constant performance contours on a Smith chart.

As advanced load-pull measurement systems gain in popularity, increasingly sophisticated capabilities have been added to Microwave Office in order to help designers deal with more and more complex sets of load-pull data. Strategic use of these

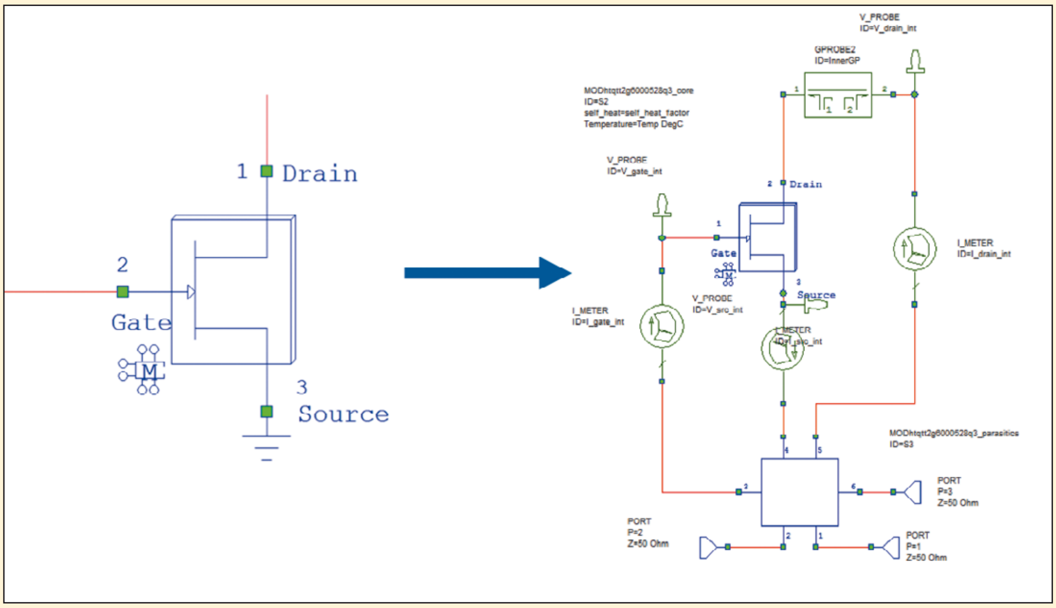

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Figure 2: Modelithics device model enables designer to measure at the package plane and at the current generator of the device

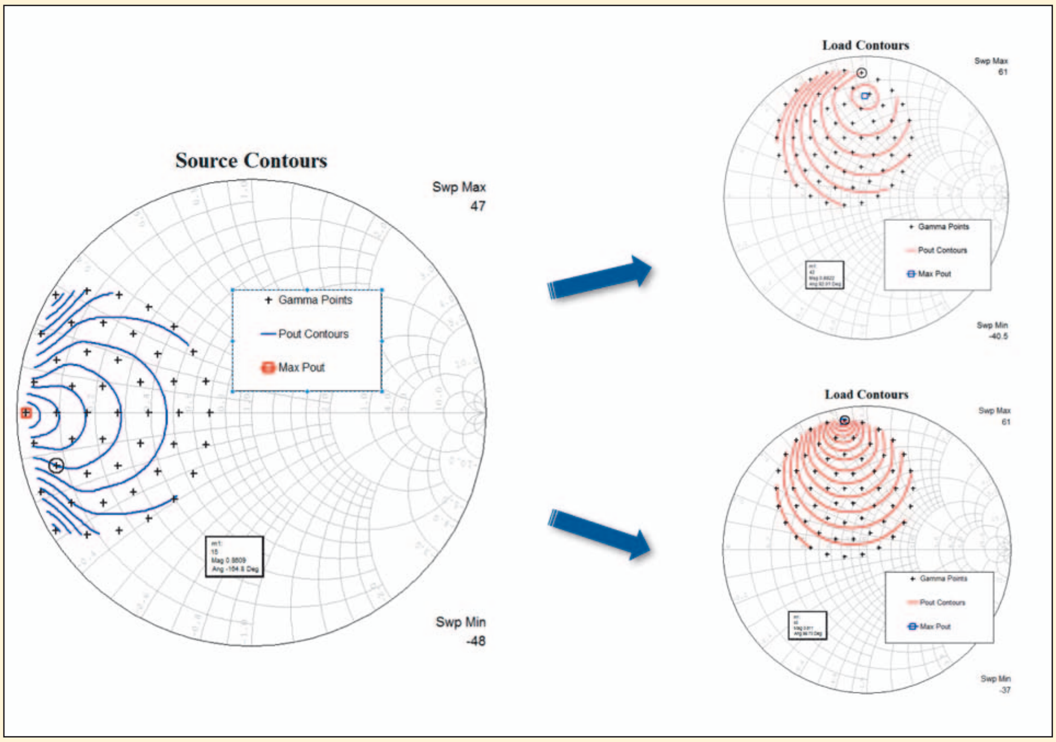

Figure 3: Impedance selected source side (left) and resulting contours (right). Changing the impedance updates the load-pull contours

tools streamlines the overall power amplifier design flow, enabling designers to eliminate guesswork and post-fabrication "tweaking" from their first-cut prototypes. The same load-pull capabilities can be applied to simulated compact device models.

Device Model and Design Goals

The example used for this application note is based on a Qorvo T2G6000528-Q3 gallium nitride (GaN) on silicon (SiC) high-electron-mobility transistor (HEMT) device with approximately 10 W at P3 dB power compression and 28 V of drain voltage operation. The bias point is Class B or very heavy Class AB (Figure 1).

A Modelithics device model for the packaged transistor was used, enabling intrinsic I-V sensing at the current generator plane of the device, which allows the designer to remove the RF effects of the package and internal device interconnects of the model through de-embedding and make IV waveform measurements at the reference plane of the device's current generator. Therefor, the measurements can be made not just at the package leads or transistor feed structure where a typical, calibrated measurement system reference plane would be defined, but also at the actual current generator of the device, right at the drain of the transistor (Figure 2). The gamma-probe element enables the user to actually plot the impedances right at this critical reference plane.

Nested Source and Load Pull

Microwave Office software simplifies designing with load-pull data by nesting together source- and load-pull results. Typically, when users are starting a device design, they need to establish the appropriate source match before exploring the first-cut load pull. Depending on the device's level of reverse isolation (S12), a non-50-ohm load impedance will change the source impedance match. Therefore, designers should initially base their source match on the input impedance of the device, terminated with the preferred load impedance, which in turn is impacted by the source impedance. Consequently, determining the optimum source and load impedances is an iterative process. One way to streamline that process is to nest together source pull and load pull, so there is a load-pull data set that contains both. For each source point there is a full set of load-pull data and for each load point there is a full set of source-pull data. As shown in Figure 3, the impedance can be selected on the source side (left) and the resulting set of contours generated on the load side (right). The impedance can be changed simply by moving markers, which will update the load-pull contours.

Conversely, on the device output, the load impedance point can be selected and the resulting source-pull contours will be shown on the right. Again, the source-pull contours are updated by moving the data marker amongst data points on the device's load reference plane. This powerful fea-

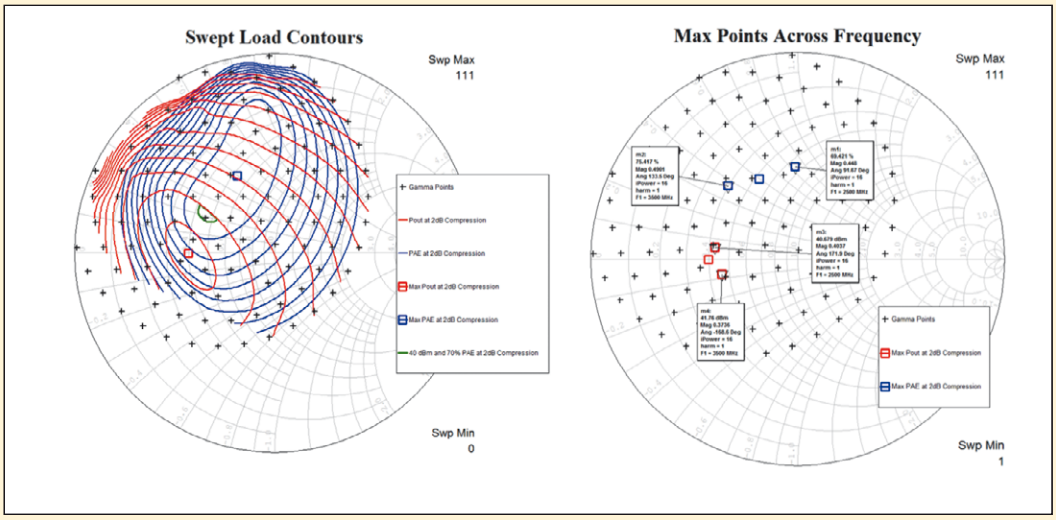

Figure 4: Microwave Office offers an overlap contour (oval shaped contour in the middle of the graph) that meets two performance parameters at the same time (left). The maximum markers point out the maximum point for any measurement across frequencies (right)

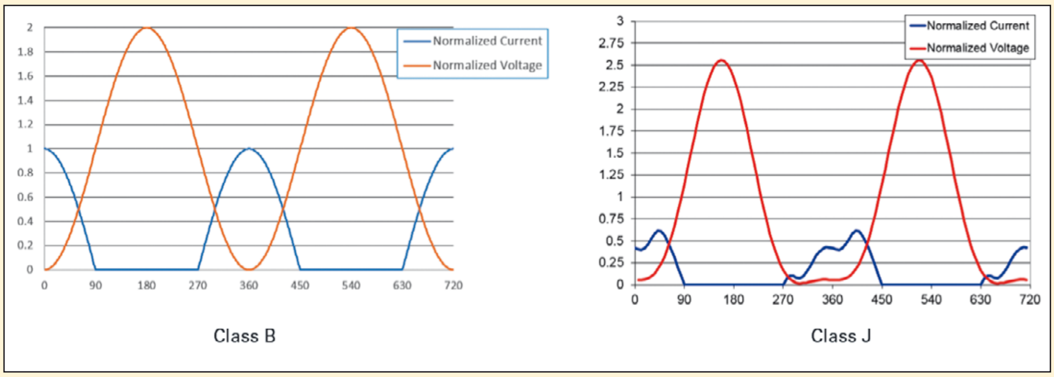

Figure 5: Class B waveforms (left) and Class J waveforms (right)

ture eliminates the need to perform iterative simulations with different source/load terminations in order to define the input and output target impedances. It is all there in one data set.

Load Pull With Frequency

Once the initial source match has been established, designers can focus on a more rigorous load-pull analysis, taking into consideration any operating conditions such as frequency or input power and performance metrics such as P1dB, PAE or ACPR. As many data points as needed can be used and can also be plotted in terms of other performance parameters, typically specific output power or specific gain compression points, rather than plotting strictly in terms of input power. In addition, Microwave Office offers an overlap contour, shown in Figure 4, as the small oval-shaped contour in the middle of the graph on the left. With the overlap contour two performance parameters are being met at the same time. The right graph shows the maximum markers that point out the maximum points for any measurement across frequencies.

Power Amplifier Overview By Class Type

Approaching the theoretical maximum efficiencies shown in Table 1 is dependent upon achieving a perfect short condition at the device's current generator plane for harmonic frequencies. In more sophisticated modes of operation like Class F, the theoretical efficiency is actually 100 percent for Class F, where the voltage and current waveforms are "squared off" and 180 degrees out of phase. Theoretically, achieving this waveform shape would require shorting infinite harmonics, which isn't at all practical, so typically 88.4 percent is used as a maximum available efficiency, achieved through the appropriate load impedances at the second and third harmonics.

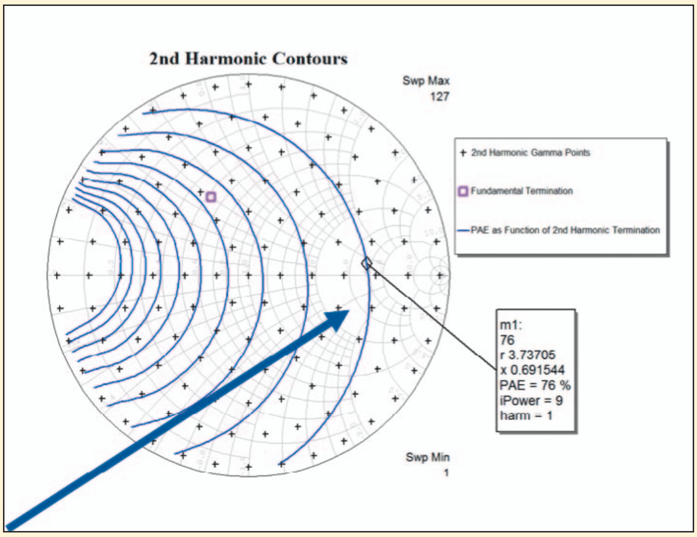

Figure 6: Harmonic load pull can be used to assess the impact of controlling the second and third harmonic terminations and easily establish an area of the Smith chart (blue arrow) for harmonic impedances to maximize device performance

Class J was introduced by Dr. Steven Cripps in 2006. It starts with a Class B bias condition and essentially adds the reactive termination at both the fundamental and the second harmonic frequencies. Therefore, the linearity impairment is less than for Class E, for instance, which is essentially a switched-mode operation.

What does this mean in terms of the waveform shape? Figure 5 shows the Class B waveforms on the left and the Class J waveforms on the right.

Class B, as noted previously, is at 180° conduction cycle. For the Class J waveforms, some harmonic content has been added, the current waveform is essentially squared off, and the time when the device has a positive voltage and is also conducting is minimized. The Class B theoretical efficiency can be reached without having to have short circuit conditions, which provides a much more practical approach.

Harmonic Load Pull

How does this fit in with load pull? Apart from fundamental load pull, Microwave Office software enables designers to perform load-pull analysis that includes load-pull contours based on termination impedances at harmonic frequencies. This allows them to quickly assess the impact of controlling second- and third-harmonic terminations on PA performance. Figure 6 shows a fixed fundamental termination on the load side with the second harmonic termination essentially being pulled around the entire Smith chart. Power-added efficiency (PAE) contours can be plotted, which

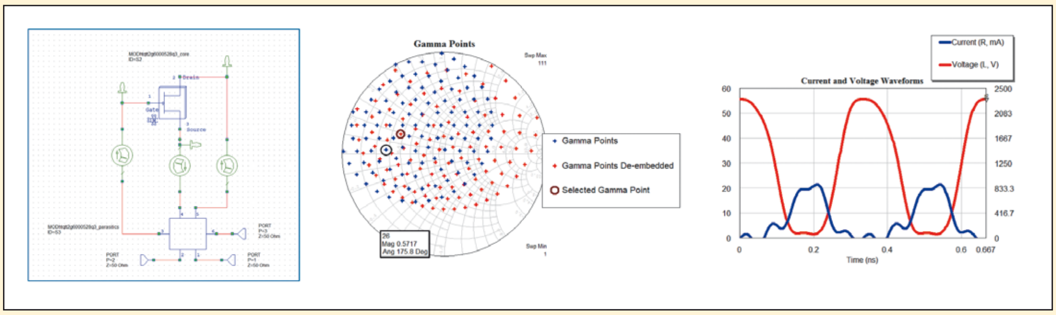

Figure 7: Microwave Office de-embedding network showing de-embedded gamma points and waveforms

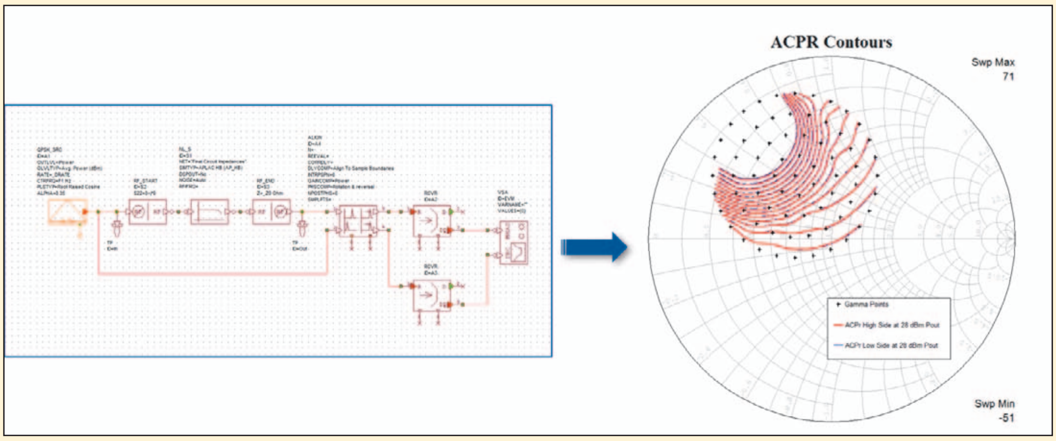

Figure 8: VSS and Microwave Office offer integrated system/circuit-level load pull. System measurements provide further impedance optimization and insight to the impact of varying load conditions

show the efficiency of the device based on its harmonic terminations and identify an area of the Smith chart where efficiency is maximized.

Class	Maximum Efficiency
A	Theoretical Efficiency 50%
B	Theoretical Efficiency 78.5%
AB	Theoretical Efficiency 50...78.5%
F	Theoretical Efficiency 88.4%

Table 1: Overview of theoretical efficiency

De-Embedding and Waveforms

De-embedding is important for studying the current and voltage waveforms at the current generator plane of the device instead of at the package leads. As noted earlier, the model used in this example enables designers to make measurements at the drain pin of the actual current generator of the device. But if the model reference plane is not at the current generator, and the designer knows the details of the internal matching elements and package or test fixture (as represented by an S-parameter block), that knowledge can also be applied in Microwave Office software by using a de-embedding network and plotting the waveforms at the current generator (Figure 7). This allows the designer to directly ascertain if Class J conditions are being achieved. In the absence of either of these capabilities –a model or a de-embedding network – nesting can be used to sweep the fundamental and second or third harmonic terminations to obtain performance contours. This provides a useful design path when de-embedding isn't possible or practical.

NI AWR software provides load-pull capability based on system measurements. This feature uses Visual System Simulator (VSS) system design software integrated with Microwave Office to contour system measurements such as adjacent channel power ratio (ACPR), error vector magnitude (EVM), and bit error rate (BER), providing insight into the impact of varying load conditions and how the device will operate under a digitally-modulated RF signal. Figure 8 shows the application of a modulated quadrature phase shift keying (QPSK) signal, although very sophisticated signals such as LTE or 5G modulated signals can also be applied to plot both circuit- and system-level contours. In Figure 8, ACPR contours for the device are being plotted.

System load pull offers the same functionality as using circuit-level load pull with an expansion of measurements commonly used in communication systems. As with circuit measurements, system measurements can be referenced to a specific output power level or any other operating condition or measurement (Figure 9) and are not limited to simply a function of the input power.

Load pull is and will continue to be an integral part of most design flows for high-power amplifiers, whether it be load-pulling device models or measured load-pull files. The unique functionality of nesting source- and load-pull contours in NI AWR Design Environment can significantly shorten the time required to design an amplifier by streamlining the iterative process of determining the appropriate impedances to present to the device's input and output terminals. De-embedding and waveform plotting is useful for understanding if the matching circuit is performing the necessary waveform shaping (squaring off) to improve amplifier efficiency. Nested fundamental/harmonic load-pull contours can be used in the cases where studying the waveform at the device model's current generator isn't practical. System-level load pull provides an additional powerful design option for engineers studying performance tradeoffs based on system measurements such as ACPR, EVM, and BER for amplifiers operating under digitally-modulated RF signals.

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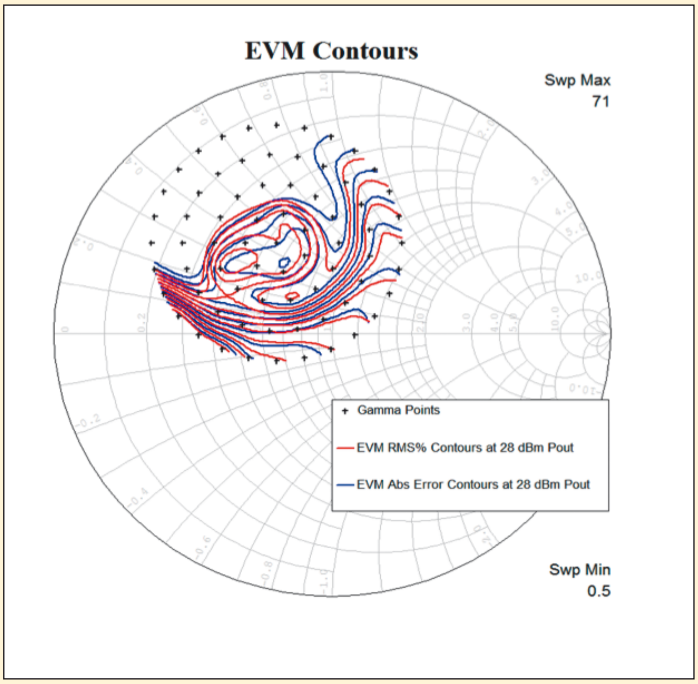

Figure 9: As with circuit measurements, system-level measurements can be referenced to a specific output power level