Assets of Source Pull for NVNA based load pull measurements

Tony GASSELING, Emmanuel GATARD*, Christophe CHARBONNIAUD*, Alain XIONG**

**AMCAD ENGINEERING – Limoges - FRANCE*

***Abstract* — This study deals with Vector Network Analyser based source-load-pull measurements. While a lot of papers demonstrated the influence of harmonic load impedances on PAE performances and time domain RF waveforms shaping, the harmonic source-pull topic has been a little bit less addressed. When using a traditional power meter based source/load-pull bench, source pull measurements are mandatory. Indeed, for a fixed power level and a given set of load impedances, the source pull optimization highlights the conditions to match the transistor's input access. Nowadays, modern Vector Network Analyser based source-load pull systems provide the direct measurements of the transistor input impedance. Thus, from the theoretical definition of any arbitrary source impedance, the mismatch calculus between input and source impedances is possible. It gives rise to a new kind of virtual source pull measurements. Some of us have called this method "magic source pull". This method and its limitations will be explained, comparison between traditional source pull and Vector Network Analyser based "magic source pull" will be provided.**

***Index Terms* — Source pull, load pull, nonlinear vector based measurements, transistor characterization, power amplifier design.**

I. INTRODUCTION

RF and microwave transistors are widely used for the design of power amplifiers. These components are in principle mismatched. Consequently, if no particular attention is given regarding the introduction conditions of these components in a given electronic circuit, the majority of the incident signal is reflected at the input of the component. This signal will thus not be amplified

Consequently, it is essential to perform impedance matching of this component input [1]. This is particularly done by matching circuits. The information needed to design such input matching circuits can be provided by an accurate transistor model, or a source pull measurement setup that makes use of tuners. These tuners make it possible to decrease the quantity of reflected signal at the input, and thus to maximize the quantity of inputted signal into the component which will be amplified thereafter [2]. A tuner is a transformer that performs a transition between the characteristic output impedance of the electronic circuit and the transistor input impedance.

A maximized signal transfer requires a prior knowledge of these two impedances. Such maximization brings into play the notions of transducer gain and power gain of the device under testing, hereinafter named DUT [3]. The power gain is the ratio between the output power provided to the load and the net input power delivered to the DUT. The transducer power gain is the ratio between the power delivered to the load and the gross power available at the input of the DUT originating from the source. Thus, the power gain corresponds to the transducer power gain when the power transfer at the input is maximal, that is to say when the impedance matching is achieved between the DUT and the source. In this condition, all the available power is transferred and injected into the DUT.

Using a traditional source pull measurement bench, for a fixed power level and a given set of load impedances, the source pull optimization provides the conditions that provide the best matching at the transistor's input path. Latest Vector Network Analyser (hereinafter named VNA) based source-load pull systems provide the direct measurements of the transistor input impedance. This makes the source pull optimization less necessary. Indeed, when designing a power amplifier, input matching circuit can be optimized using the transistor input impedance knowledge. The PA designer just need to design an input matching circuit that provides a source-impedance equal to the conjugated value of the transistor's input impedance.

II. TRADITIONAL SOURCE/LOAD PULL

The technique of traditional source/load pull is illustrated in Fig1. This setup is a power-meter based measurement system. The power meters are connected to the DUT through directional measurement couplers.

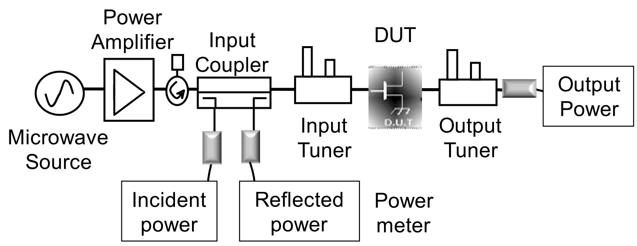

Fig. 1. Schematic of a traditional load pull measurement system

Using this setup, the source impedance could be adjusted at the input of the DUT in order to minimize the reflected power or to maximize the transducer power gain. For "load pull" measurements, the technique could be similarly applied at the output by the mean of the output tuner in order to maximize the power delivered to the load. If so, the optimization results from the maximization of the transducer power gain.

978-1-4673-1231-8/12/$31.00 ©2012 IEEE

Because the tuners are pre-characterized, source and load impedance information can be provided by the tuners during the optimization. Thus, for a given power level, the transducer power gain optimization result gives the value of the optimal source impedance. The complex value of the input impedance of the transistor (hereinafter named Zin) can be inferred from the source impedance complex value (hereinafter named Zsource), without ever having been directly measured. Indeed, for maximum transducer power gain, the condition is:

$$Zin = Zsource^{*} \qquad (1)$$

The main drawback of this method is as follows. To design power circuits, RF and microwave transistors are often driven into saturation. Because these devices are nonlinear, for a fixed set of bias voltages, the input impedance value of the DUT depends on both level of the power which is delivered and impedance that load the DUT as shown on Fig. 3. Thus, theoretically, for each different level of power delivered to the DUT and for each set of load impedances, a maximum transducer power gain would be achieved by a new source pull optimization. This is why in practice, during source pull measurements, the perfect matching at the input is never reached, but according to measurement targets, a tradeoff is often defined to match the DUT at low, medium or high transducer gain compression.

Consequently, the input impedance of the transistor is never known on the full range of the power sweep. This lack of information hides the level of mismatch between the input impedance of the DUT and the source impedance for each power level. This is why traditional source/load pull setup only provides transducer power gain data, and not absolute power gain performances.

III. VNA BASED SOURCE/LOAD PULL

The technique of VNA based source/load pull is illustrated in Fig. 2. In this setup, input and output bidirectional measurement couplers are placed between the tuners and the DUT. These ones are connected to the VNA receivers [4] [5].

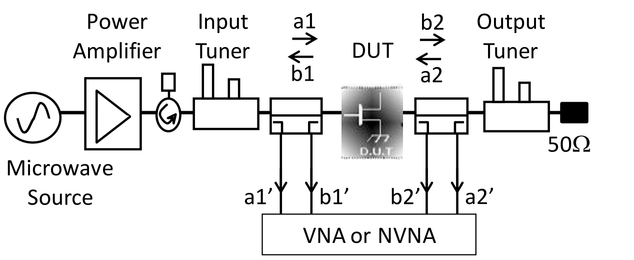

Fig. 2. Schematic of a VNA based source/load pull measurement system

The VNA is the main measurement unit. Once calibrated, this one provides both absolute power and impedance measurements. To the contrary of traditional source/load pull system, the DUT input impedance is now measured for each power level and for each set of load impedance rather than derived from transducer power gain optimization. This opens a new field of application.

Because of the direct measurement of the DUT input impedance, source pull optimization is less necessary. Indeed, when designing a power amplifier, input matching circuit can be designed from the transistor's input impedance knowledge. The power amplifier design can be driven from an input matching circuit that provides as source impedance equal to the conjugated value of the transistor's input impedance.

Thus, the source tuner is mainly considered as a matching element just needed to boost the input power rather than providing a specific knowledge about the transistor intrinsic performances.

Critics of this type of measurement bench say that measurement coupler losses will reduce the minimum impedance that could be provided to the DUT. This is true, but usually, if dealing with 1 or 2Ω load impedance order of magnitude, a taper has to be designed to pre-match the transistor. If not, the load tuner need to act as a short circuit to provide a low impedance, and power measurements through this quasi-short-circuit will suffer from a lack of accuracy. Looking at the source tuner, the good news is that low source impedances close to short circuit do not need to be provided anymore when dealing with the method presented here.

IV. TRANSISTOR INPUT IMPEDANCE MEASUREMENT

For model validation, is it really important to use a VNA based load pull rather than a traditional load pull because the input impedance variation versus power level and load impedance must be reproduced by the model. VNA based load pull enables measurement/simulation comparisons of the DUT input impedance variation.

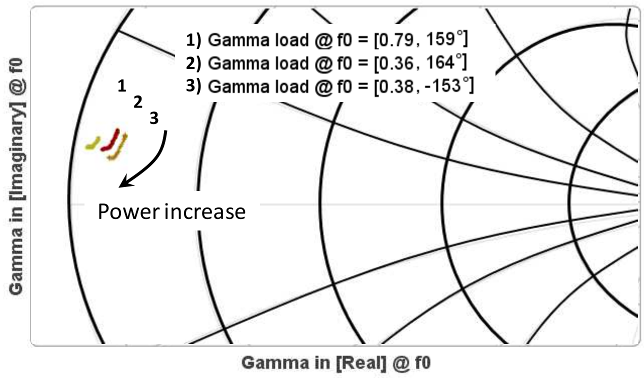

Fig. 3. Example of transistor input impedance variation versus power level and load impedance

If the model is able to reproduce this kind of behavior, the simulation will be accurate when looking at the input return loss performances or transducer power gain as a function of the source impedance. This is quite important when linearity is a constraint for the PA design. Indeed, because of the model accuracy, the simulation of the input impedance can be used for the calculus of the input mismatch for each power level and for each load-impedance, and for the simulation of the transducer power gain compression.

V. CONCEPT OF MAGIC SOURCE PULL

Sometimes, PAs are designed only from source/load pull measurements, even without transistor model availability. The intend of the measurement is not really to know the transistor input impedance variation versus power level, but rather to know which source impedance must be provided to meet the PA specifications. In this configuration, the following methodology is quite useful because instead dealing with time consuming source pull optimization, only one power sweep per load impedance can be enough to provide an infinite number of conditions to optimize the input matching [6]. Indeed, one advantage is to avoid the necessity of carrying out a measurement for a given source impedance, in order to know the DUT performances for this source impedance. For example, using a traditional source/load pull system, if the user wanted to know the performances obtained for X different source impedances, X measurements would need to be carried out by changing this source impedance every time. Furthermore, once the measurements carried out, it is difficult to know a posteriori the results which would have been obtained for other source impedances. Some parameters are in fact quite sensitive to the variation of the source impedance, such as transducer power gain expansion according to the power level.

To the contrary of a traditional source/pull system, using the method presented, the source impedance is defined theoretically, and not physically. This makes possible to even avoid using a tuner at the input of the DUT. Based on this theoretical source impedance, it is possible to calculate the theoretic available power that would be provided by this source. This assumption is based on the postulate that the DUT is perfectly unilateral, namely that the source impedance exhibited does not impact the output impedance exhibited by the DUT.

Also, this method makes it possible to define the optimal operating conditions of the transistor according to several parameters which may be transducer power gain, gain compression, power efficiency. Performance acquisition of each parameter for the source impedance is determined according to the theoretical source impedance, the measured input and load impedance at the DUT, as well as the net power injected at the input and the output power measured at the DUT references planes.

V. THEORY AND EXAMPLE OF MAGIC SOURCE PULL

In this example, the DUT is a GaAs field effect transistor. The testing fundamental frequency is 4GHz. The fundamental load impedance Zload exhibited at the output of the DUT is fixed (81.3+J51.6Ω). Thank to the use of cascaded load tuners, harmonic impedances at 2f0 and 3f0 have been adjusted to 50Ω. The net input power (hereinafter called P_{IN}) delivered to the DUT is fixed.

Using the magic source pull concept, the value of the calculated available gross power (hereinafter named P_{SOURCE}) is calculated from the measurement of the delivered power P_{IN}, from the transistor input impedance measurement "$Z_{IN}=R_{IN}+JX_{IN}$", and from the theoretical definition of the Generator Source impedance "$Z_G=R_G+JX_G$". From these three values, the electromotive force "E_G" of the equivalent generator is calculated, without needing to physically put in place such impedance "Z_G" to carry out the measurements, in order to avoid any inaccuracies and any limitations of a range of values generated by a source tuner. This equivalent Generator source power is given by:

$$E_G{}^2 = 2\frac{P_{IN}}{R_{IN}}[(R_G + R_{IN})^2 + (X_G + X_{IN})^2] \qquad (2)$$

$$P_{SOURCE} = \frac{1}{8}.\frac{|E_G|^2}{R_G} \qquad (3)$$

For each given source impedance theoretical value, the transducer power gain is thus directly derived from the ratio between the output power delivered to the load and the calculated available source power related to the source impedance Z_G of the equivalent generator:

$$Gain\_Trans = \frac{P_{OUT}}{P_{SOURCE}} \quad (4)$$

Other characteristics of the DUT associated to a given environment, such as the transducer power efficiency, transducer gain compression, may also be derived by calculation. By a posteriori determining the results obtained for another source impedance, it is thus advantageous to be able to attain several simultaneous objectives – for example a given output power associated to a compression of maximum transducer power gain-, whereas the traditional testing method requires the measurement of the transducer power gain for every source impedance synthesized by the source tuner.

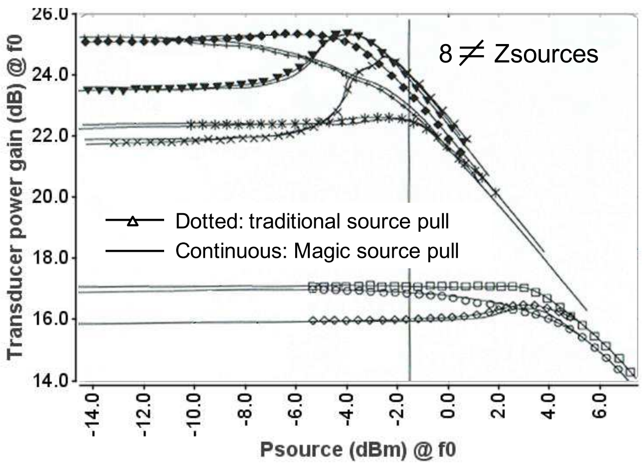

Fig. 4. Traditional source pull measurement and Magic source pull comparison at 4GHz on GaAs FET transistor for a given ZLoad.

Fig.4 illustrates a comparative drawing of transducer power gain measurements and calculation given by the traditional approach and the methodology presented here for different source power levels. Curves measured with a traditional source pull are dotted. Both methods show a good agreement, even when gain expansion is highlighted.

The curves that display some transducer gain expansion correspond to the conditions where the source impedance was tuned close to the conjugate value of the transistor input impedance measured at high power levels. In these conditions, the higher the power level, the better the matching between Z_{IN} and Z_{SOURCE}. To the contrary, the curves that display some early transducer gain compression correspond to the conditions where the source impedance was tuned close to the conjugate value of the transistor input impedance measured in low power conditions. Thus, the higher the power level, the higher the mismatch between Z_{IN} and Z_{SOURCE}. The three low gain curves are given for source impedance on 50 Ohms plus two sources impedances on the opposite side of the smith chart (far from the optimal area).

By way of example, these curves are obtained for eight source impedances, either synthesized by a source tuner according to the traditional method of given theoretically according to the magic source pull method. In this example, for each curve, the theoretical source impedance corresponds to the value of the source impedance measured during the use of the classical source pull bench. Thus, it appears that the method used makes it possible to reproduce in a calculated manner the measured transducer power gain values obtained from the entire scanning of powers of the eight synthesized source impedances. It is thus justified to apply this calculation method for other ranges of impedance and for any type of characteristics of the DUT if the source impedance intervenes only on the matching conditions at the input of the DUT.

Nevertheless, if the internal source impedance also affects the intrinsic operation of the DUT, this technique only constitutes an approximation tool, but provides relatively reliable results that can be used to speed up the source pull measurement process. It is quite simple to check if the source impedance modifies the transistors intrinsic characteristics or not. For verification, rather than plotting the transducer power gain versus the available source power for different source impedances as illustrated on Fig. 5, the true power gain versus delivered input power for the same source impedances can be displayed as illustrated on Fig. 6. The following example is given for a GaN FET transistor measured at 3.5GHz. For record, the true power gain is directly derived from the ratio between the output power delivered to the load and the delivered net input power to the transistor, whatever the generator internal source impedance value "Z_G" .

$$Gain = \frac{P_{OUT}}{P_{IN}} \qquad (5)$$

In these conditions, when the real source impedance is far from the usual source impedance close to the conjugate value of the transistor input impedance, the power delivered by the power amplifier driver need to be higher than the usual power because of the significant mismatch between the source tuner and the transistor.

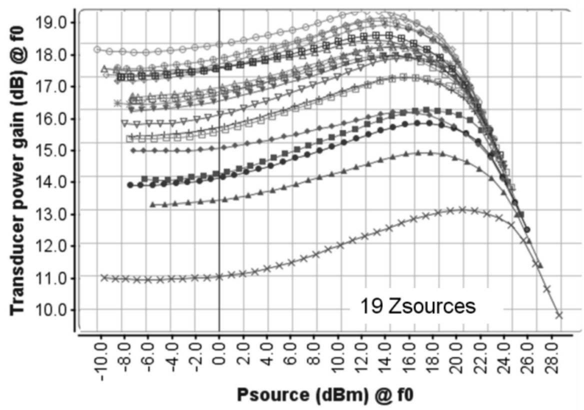

Fig. 5. Transducer power gain measurement versus available input power for 19 different sources impedances

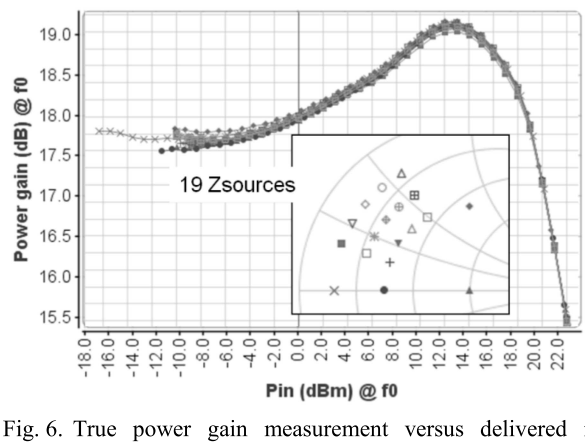

Fig. 6. True power gain measurement versus delivered input power for 19 different sources

Figures 5 and 6 highlight the fact that the source impedance merely impact the transducer power gain (variation of 7dB) while the true power gain variation is lower than 0.2dB for sources impedances spread over the Smith chart. In practice, the first power sweep can be made for source impedance close to 50 Ohms, then the source tuner may be used to match the PA output impedance to the transistor input impedance to get conditions given by equation (1).

IV. Time Domain LP Measurements

To complete this study, additional Nonlinear VNA based load pull measurements have been done. The load pull setup presented was upgraded with a comb generator that provides an absolute phase reference in order to measure the harmonic signals (f0, 2f0, 3f0) calibrated in magnitude and phase. This enables to get microwave measurement of the RF load line in time domain [7-9]. Previously, pulsed IV and Pulsed S parameters have been done in order to extract the lineal model of the transistor under test. The aim was to extract the parasitic extrinsic elements of the transistor, in order to have a deembedding of the measurements into the current source intrinsic reference planes of the transistor.

The aim was to observe the RF load line in the intrinsic planes as a function of the different sources impedances spread over the smith chart. Once again, the goal was to study the influence of the source impedance over the intrinsic characteristic of the transistors.

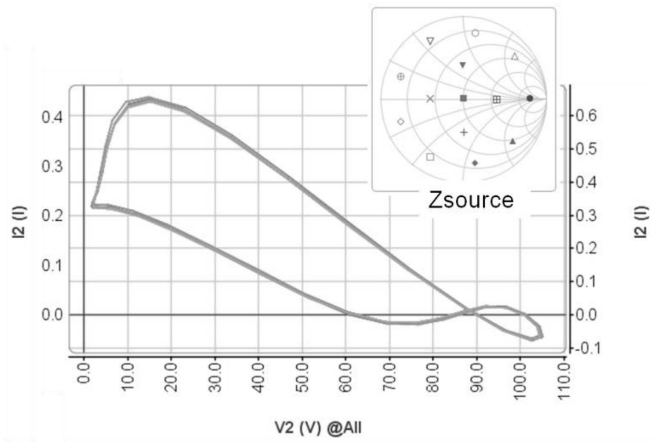

Fig. 7. RF load line as a function of source impedances

The RF load line comparison is made for various Zsource values, but for the same amount of delivered power into the transistor. It can be observed that the RF load line is not modified by the source impedance value. Because of the limited number of harmonic measured, the output current waveform has some negative values. More accurate waveform could be obtained by increasing the number of harmonic measured. While this is no more than an empiric experiment, this example highlight the fact that the source impedance does not change the intrinsic transistor characteristics used for this experiment, whatever how the power was injected into the transistor, this confirming the interest of the magic source pull methodology.

VII. Conclusion

The work presented here highlights the main advantages of "magic source pull" measurement methodology that could be offered by VNA based source/pull measurement bench. This method offers a quite interesting tool which reduces significantly the time spent on source/load measurements. In addition to the flexibility that is provided, considering the cost of the equipment to be used and the need of qualified resources to conduct traditional source/pull measurements, this method offers a great advantage to increase source/pull measurement return on investments for Power Amplifier Designers.

Acknowledgement

Authors acknowledge Maury Microwave and Agilent Technologies Corporations for the technical support provided to conduct this work.

References

[1] B. Becciolini, "Impedance Matching Networks Applied to RF Power Transistors", Freescale Application Note AN721, Rev. 1, 10/2005

[2] Maury Microwave, "Automated Tuner System," Operating Manual MT993-2 Rev L, pp. 7-1,2,3, pp. 8-1,2, Appendix 4 and 6, June 2002

[3] H.Y. Pan, et al., "A Novel Interpretation of Transducer Power Gain by Optical Analogy," Microwave and Optical Technology Letters / Vol. 31, No. 2, October 20 2001

[4] A. Ferrero, V. Teppati, "A complete measurement Test-Set for non-linear device characterization" ARFTG Conference Digest-Fall, 58th, Nov. 2001

[5] S. Dudkiewicz, "Vector-Receiver Load Pull Measurement," Microwave journal – Special Report, p. 88 - 98, February 2011.

[6] F. Verbeyst, M. Vanden Bossche, "Speed up power amplifier design by fast source-pull, real-time load-pull and accurate measurement-based behavioural models", Microwave journal - Editorial, p. 24 - 30, November 2005.

[7] D. Barataud, et al., "Measurement and Control of Current/Voltage Waveforms of Microwave Transistors using a Harmonic Load-Pull System for the Optimum Design of High Efficiency Power Amplifiers," in IEEE Transactions on Instrumentation and Measurement, Vol 48, No. 4, 1999

[8] F. De Groote, J. Verspecht, D. Barataud, J.-P. Teyssier, "An improved coupling method for time domain load-pull measurements," in European Microwave Conference, Vol 1, 2005

[9] H. Mashad Nemati, A.L. Clarke, S.C. Cripps, J. Benedikt, P.J. Tasker, C. Fager, J. Grahn, H. Zirath, "Evaluation of a GaN HEMT transistor for load- and supply-modulation applications using intrinsic waveform measurements," Microwave Symposium Digest (MTT), 2010.