Impedance Synthesis Algorithms for Hybrid Harmonic Load Pull

Bryan Hosein and Timothy Beauchamp
Focus Microwaves
1603 St Regis, Dollard des Ormeaux, Quebec, H9B 3H7 Canada
Tel: 514-684-4554
E-mail: bryan@focus-microwaves.com

Abstract — **This document presents a hybrid harmonic load pull system and the associated impedance synthesis algorithms. Specifically, these algorithms are used to combine passive harmonic impedance synthesis using electromechanical tuners with open loop active injection to present a combined hybrid load impedance to a device under test (DUT). The key advantage of said algorithms is that they allow any DUT impedance to be matched with a minimum of injected power.**

Keywords — active injection, electromechanical tuner, harmonic impedance synthesis, load pull, open loop, virtual load.

I. INTRODUCTION

In RF device characterization traditional passive load pull [1] has been used as a standard method to measure performance in non-linear conditions. In traditional passive load pull a device under test (DUT) is driven with a signal source and its performance is measured under different matching conditions. As such, impedance control instruments (tuners [2]) are used to synthesize the impedance presented to the DUT at the frequency of operation. Such device testing can be used to determine the optimum operating conditions where the DUT produces the maximum power, gain, or other operating criteria. Additionally, in more advanced load pull testing the harmonic impedances can also be controlled (typically at the output of the DUT) in order to optimize DUT power added efficiency (PAE) performance [3]. As such the ability to accurately and reliably control the fundamental and harmonic impedances presented to the DUT is essential. In a passive load pull system, this need can be fulfilled using a multi-harmonic (MPT [4][5]) type tuner or using a triplexer and multiple tuners for each frequency of interest. In an active load pull [6] system this need can be fulfilled using active injection impedance control (at multiple frequencies). This document presents the conventional methods and their inherent limitations and shows how these limitations can be overcome using the specialized hybrid (combination of passive and active) impedance synthesis algorithms presented herein. Additionally, as a demonstration some actual measurement data is presented.

II. LOAD PULL SETUP

In the following block diagram (Fig. 1) the proposed hybrid load pull setup is depicted. This setup is essentially a combination of passive and active load pull configurations that allows the simultaneous measurement of the DUT performance and the real-time impedance presented to the DUT.

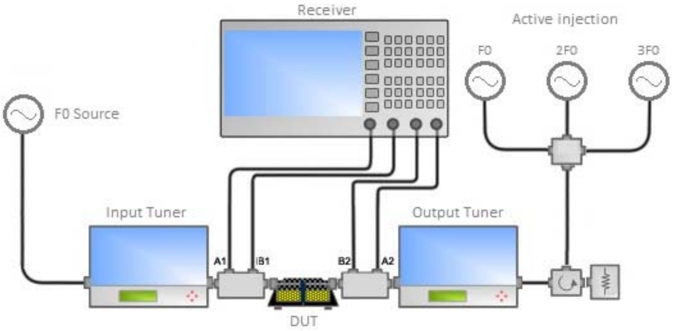

Fig. 1: Hybrid Harmonic Load Pull setup

In Fig. 1, the F0 Source (left hand side) is synchronized with each of the individual Active Injection sources (F0, 2F0 and 3F0 sources as depicted). The input and output tuners are placed before and after the DUT and are used to present different impedances to the DUT. Also, the incoming and outgoing (A and B) waves are sampled through the couplers and measured using the receivers of a vector network analyzer (VNA). These wave measurements can be used to determine both power quantities and, if appropriate phase reference calibration is used, time domain waveform reconstruction [7]. Therefore, both Γin (reflection coefficient looking into the input of the DUT) and Γload (reflection coefficient looking into the load presented to the DUT) can be determined [8]. Specifically:

$$\Gamma\text{in} = B1/A1 \qquad (1)$$

$$\Gamma\text{load} = A2/B2 \qquad (2)$$

In the analogous passive harmonic load pull system (compared to Fig. 1) the active injection path is not present and therefore the maximum Γload achievable by the system is limited to the physical limits of the output tuner (in this case an MPT which is capable of controlling F0, 2F0 and 3F0) and the losses between the tuner and the DUT. The latter is particularly important as the frequency of operation increases. Moreover, such limitations may prevent measurement of the

DUT at the optimum load matching condition. On the other hand, in the analogous active load pull system, the output tuner is not present (as compared to Fig. 1) and in order to present a high Γload (approaching |Γ| = 1) a very large amount of power is required (relative to the output power of the DUT at the given frequency) to present the optimum matching condition; particularly when Zout is very low. Such power requirements are often prohibitively expensive and in many cases completely unfeasible. These limitations lead to combining both methods to achieve the optimal solution, which is the hybrid system. More specifically, the goal is to combine the passive and active load pull systems whereby Γload presented to the DUT uses a combination of the passive and active to synthesize the target impedance at each frequency of interest. The method for such combination and the analysis of its advantages when compared to the aforementioned conventional passive and active load pull systems is presented in the next section.

III. IMPEDANCE SYNTHESIS ALGORITHMS

The combination of passive and active impedance synthesis techniques in the hybrid harmonic load pull system requires specialized software control of both the harmonic tuner (MPT) and the active injection sources. Specifically the goal is to synthesize an intermediate Γload with the passive tuner (Γpload) and inject power into the output of the DUT at a specific phase such that the Γload target is reached with the least active injection power possible. Upon close examination of the behavior of the system it becomes apparent that on the one hand the required active injection power decreases (in the DUT reference plane) as Γpload approaches the target Γload. On the other hand as the magnitude of Γpload increases (as will necessarily occur when the target Γload approaches 1) the loss of the output tuner increases. Therefore the intermediate reflection coefficient is chosen to be the optimized combination between minimizing the loss of the output tuner and synthesizing a Γpload that is close to the target Γload. In a practical sense this means that Γpload will be in phase with the Γload target with a lower magnitude (that is determined based on the tuner loss as per its calibration). This is depicted in Fig. 2 below.

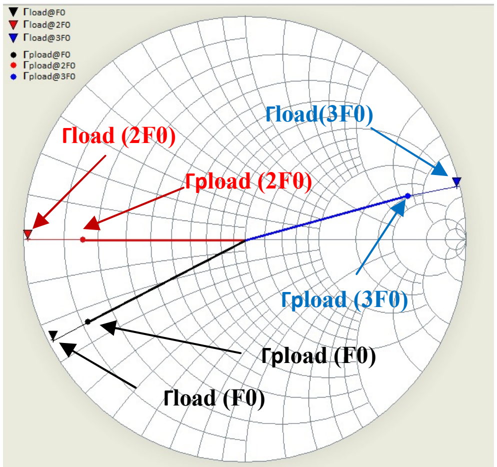

Fig. 2: Hybrid Impedance Synthesis (Γload and Γpload)

The hybrid method of impedance synthesis therefore adjusts the output tuner to the optimal impedance state for all frequencies of interest and then iteratively adjusts the active injection sources, one at a time, starting with F0, to reach the target impedance at each frequency. After each iteration, the current total Γload is measured (based on A2 and B2) as depicted in Fig. 3.

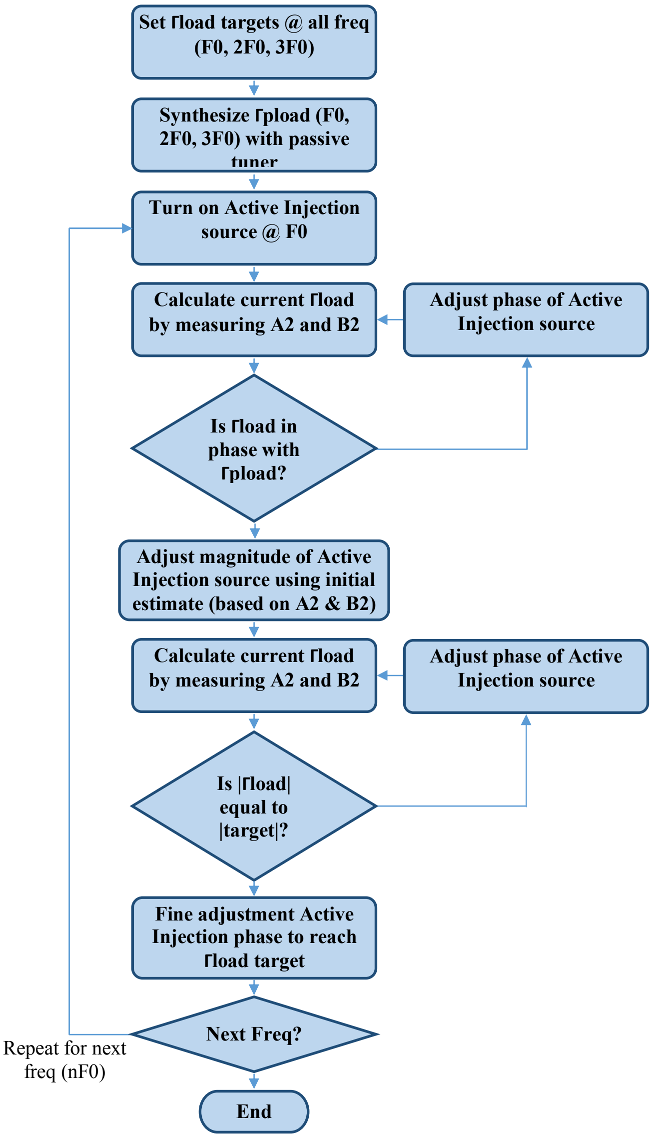

Fig. 3: Flowchart for hybrid impedance synthesis

Additionally, as a speed optimization of this search, the iteration step size of the active sources can be estimated (and adjusted dynamically) based on the most recently measured values of A2 and B2. This optimization greatly reduces the number of iterations needed. Lastly, in order to ensure the safe operation of the DUT some additional precautions (in the iteration procedure) can be used to prevent the DUT from being presented with |Γload| > 1. Using this method of hybrid impedance synthesis allows for the reliable and efficient control of Γload anywhere on the Smith Chart and therefore allows matching of the DUT even when Zout (output impedance of the DUT) is very low (see Fig. 4 below) without the need for very large active injection sources relative to DUT output power.

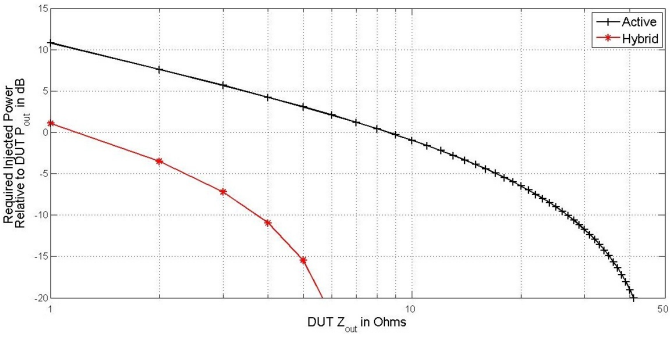

Fig. 4: Injected Power (relative to DUT output power) required to match a DUT as a function of Zout DUT: Active versus Hybrid (with |Γpload| = 0.75)

In Fig. 4, the required active injection power (available to the DUT at the output) to match a given DUT is shown as a function of Zout. Of particular importance is that for a DUT with Zout = 1 Ohm, 12x its output power (~11 dB higher) is needed to match the DUT using active impedance synthesis. On the other hand the power required using the hybrid method described is similar to (~1.25x or ~1 dB higher than) the DUT output power. Note that this calculation does not take into account any losses between the output of the DUT and the Active Injection sources (as per Fig. 1). Therefore source power required will be even higher (depending on said loss).

IV. MEASUREMENT RESULTS

Using the above described hybrid harmonic load pull system and related impedance synthesis algorithms the following measurements were performed to compare and contrast passive harmonic load pull versus hybrid harmonic load pull.

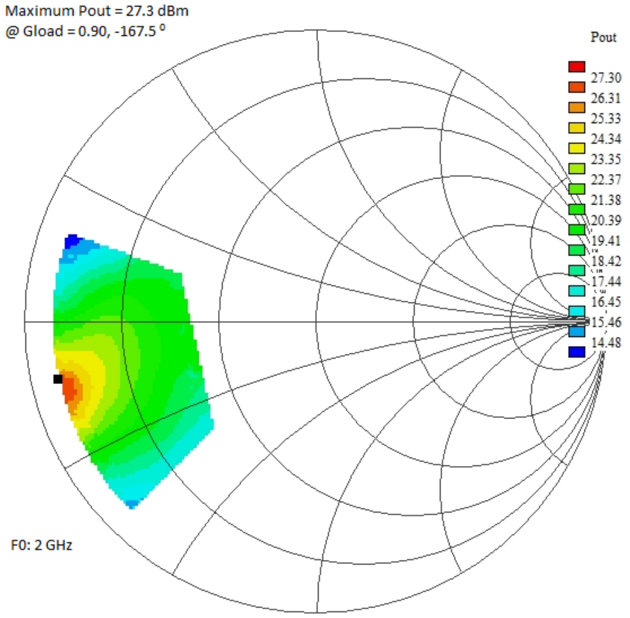

Fig. 5: Passive Load Pull Contours for an LDMOS Transistor

Note that in the above passive load pull case, the maximum output power measured was 27.3 dBm at Γload = 0.90, -167.5 degrees. However based on the shape of the contours, it is evident that the DUT is not yet matched. The figure below shows the same DUT when tested using hybrid load pull.

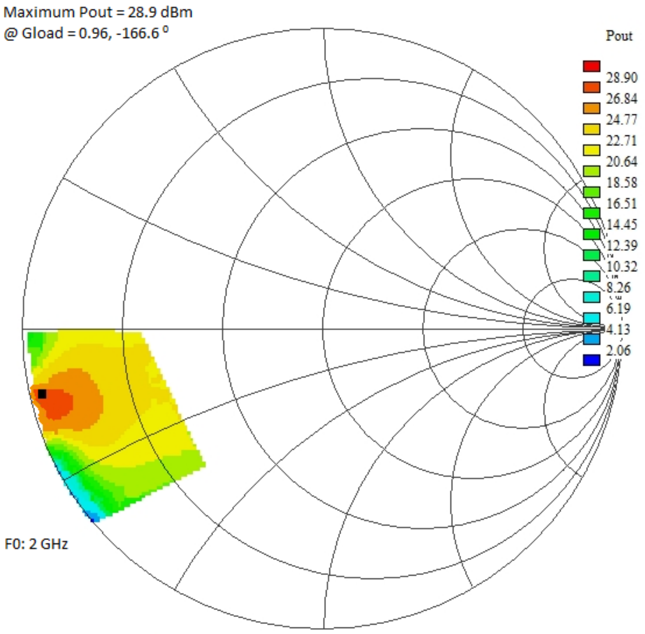

Fig. 6: Hybrid Load Pull Contours for the LDMOS Transistor of Fig. 5

In the preceding Figure, using hybrid impedance synthesis the maximum measured output power is 28.9 dBm at Γload = 0.96, -166.6 degrees. Additionally it is worth noting that based on the shape of the contours that this measured maximum represents the DUT performance under matched conditions.

Lastly, the effect on PAE of passive versus hybrid harmonic load pull was measured by performing a 2F0 phase sweep with the Γload @ F0 fixed. The 2F0 harmonic sweep was performed with a magnitude of Γload @ 2F0 = 0.8 (the maximum gamma under passive conditions) for 360 degrees. The hybrid harmonic sweep was performed at Γload @ 2F0 = 0.95. As is shown in the Figure below, the efficiency measured using hybrid harmonic load pull was approximately 3% higher.

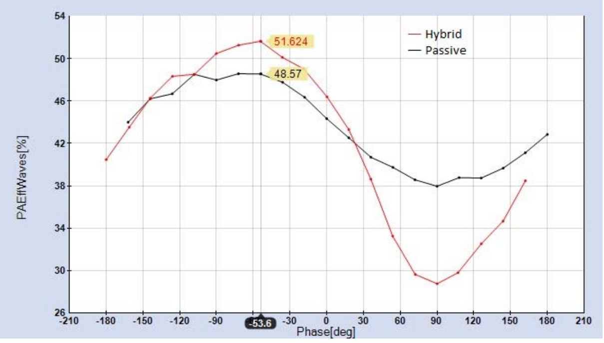

Figure 7: Effect of Harmonic Load Pull on Power Added Efficiency

V. CONCLUSION

Harmonic load pull using the described hybrid impedance synthesis algorithms offers significant advantages over the currently used passive or active load pull systems. This is due to the ability of the hybrid system to measure a given DUT up to $|\Gamma load| = 1$ (compared to pure passive systems) and the removal of the need for very large injected powers (compared to pure active systems). Moreover the practical measurement data presented are in agreement with such a statement.

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