A simplified active load-pull behavioral model for power amplifiers

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Abstract To account for load impedance variation, the extraction methods of conventional nonlinear behavioral model require complex and expensive load-pull system. In this letter, a simplified behavioral model for power amplifier (PA) is demonstrated using nonlinear vector network analyzer (NVNA) only for data extraction. An incident signal at fundamental is added in the output of PA as a disturbance signal, and thus load reflection can be realized when its amplitude and phase are swept as active load-pull system does. To increase the robust of the model, a dynamic sweeping method of output incident signal is proposed which proved can cover most of the areas on the fundamental reflection coefficient chart. This method reduces the variables of the nonlinear behavioral model while dramatically simplify the measurement architecture and reduce the cost of modeling.

Key words: nonlinear, behavioral model, power amplifier, active load-pull

Classification: Power devices and circuits

1. Introduction

In order to optimize the radio frequency (RF) system performance by EDA tools, it is necessary to fully evaluate its performance in system level, which requires accurate models for each circuits [1-3]. Circuit models, composed by compact or numerical active and passive devices models, are time consuming and poor convergence for system level simulation [4-6]. As a result, circuit models are rarely used directly in high integrated system simulation. On the contrary, behavioral model has been shown much better accuracy and efficiency, and are good for intellectual property (IP) protection, so it has been widely used in recent years [7-9]. However, the modeling of behavioral model is usually complicated and require expensive measurement systems, especially for RF power amplifiers [10,11]. After polyharmonic distortion (PHD) model [12,13] was proposed, its theory was widely accepted and quickly applied to PA modeling [14-16]. The PHD model was commercialized by Agilent Technologies (now Keysight Technologies) and named X-parameter. X-parameter can take into account the nonlinear behaviors of PA working near the large signal operating point (LSOP). The excitation of input signal is large to keep PA's LSOP, while the disturbance signal for input/output port is small, and then the responses of disturbance signal are linearly superimposed. The limitation of this situation is that it cannot consider big output mismatch of output port, which will change the LSOP of PA. Cardiff model [17,18] is proposed to overcome this problem. A diagram of Cardiff model is shown in Fig. 1. A fundamental incident signal \( a_{2,1} \) is added in the output of PA, which can characterize the mismatch of the load. And scattered waves including high order harmonics named \( b_{1,h} \), \( b_{2,h} \) are recorded. The relationship of incident and scattered waves reflect the characteristics of PA.

![Fig. 1. Travelling waves’ relationship of PA for Cardiff model.](image)

In order to consider the load mismatch effect of PA, load impedance or load reflection coefficient is added to LSOP as a variable. Thus a load pull system is required for model extraction, which increases the complexity and the cost of the test system [19-21]. When load impedance is near 50 Ohm, X-parameter accurately predicts the nonlinear characteristics of PA. However, if the load impedance deviates far from 50 Ohm, load-dependent X-parameter needs to be used in simulation[22]. Using passive load-pull system and nonlinear vector network analyzer (NVNA)[23], load-dependent X-parameter can be extracted. After the LSOP is fixed, since X-parameter defines the relationship between the incident waves and the scattered waves in fundamental and harmonics, the influence of the secondary and third harmonic load impedance can be considered to a certain extent [24]. The extraction flow of Cardiff model is fixing the amplitude of \( a_{1,1} \), and sweeping the amplitude and phase of \( a_{2,1} \), then obtaining the relationship of incident and scattered waves [25]. Cardiff University's active load-pull system [26] is used to inject coherent signals to fundamental, second and third harmonics respectively to simulate load-pull system.
Unlike passive load-pull system, the active load-pull system does not reflect the signals by tuner, but absorbs the output signal of PA by setting the appropriate load impedance. Then injects the fundamental and harmonic signals by adjusting their amplitudes and phases to cover the area in reflection coefficient circle [27].

Load-pull system is needed both in the extraction of load-dependent X-parameter and Cardiff model. Either passive or active load-pull systems is costly and complex, which increases the difficulty of model extraction

In this letter, an improved polynomial behavioral model for RF PA is proposed: the fundamental output incident \( a_{2,1} \) is used not only as a disturbance signal, but also as a variable of the active load-pull to determine the load impedance. This method can play the same role as a tuner for load-pull, but without adding additional cost. This letter also introduces the extraction method of this improved model, and carries out simulation and measurement verification of an amplifier.

2. Behavioral model principle and extraction method

2.1 The principle of behavioral model

For a PA in certain DC bias condition (DCbias), the incident and scattered waves of the input and output ports are extracted. After performing Fourier expansion on the incident signals \( a_{n,h} \) and the scattered signals \( b_{n,h} \), where \( n \) is port number and \( h \) is harmonic order, and combining the similar terms[28], the scattered signals can be expressed by

\[
b_{n,h} = P_1^{\frac{\text{m}(n+1)/2}{\text{m}+\text{m}/2}} K_{n,h,m} \left( \frac{Q_1}{P_1} \right)^m
\]  

(1)

where, \( K_{n,h,m} = \frac{\text{DCbias},[\text{a}_{1,1}],|\text{a}_{2,1}|, P_1 = |\text{a}_{1,1}|, Q_1 = |\text{a}_{2,1}|, \) and \( m \) is the polynomial order.

The \( K_{n,h,m} \) coefficient is only related to DUT’s DCbias and the amplitudes of \( a_{1,1} \) and \( a_{2,1} \). The phase of \( a_{2,1} \) (Q1) could be swept uniformly from 0 to 360 degrees, and the sweeping number is at least the same with the number of \( K_{n,h,m} \) coefficients. Then a matrix equation of \( b_{n,h} \), \( K_{n,h,m} \), and \( Q_1/P_1 \) can be obtained. Using least squares method, \( K_{n,h,m} \) coefficients can be obtained. In this letter, the polynomial order is fixed to 5.

For this polynomial model, only the reflected wave of fundamental signal is used as an input variable, so the model can be extracted using only fundamental load-pull system, and reverse incident signal \( a_{2,1} \) is controlled to realize this active fundamental load-pull system.

2.2 Extraction flow of proposed method

For the output of a PA, fundamental incident wave is \( a_{2,1} \), and fundamental scattered wave is \( b_{2,1} \), then fundamental load reflection coefficient could be defined as Eq.(2):

\[
\Gamma_{2,1} = \frac{a_{2,1}}{b_{2,1}}
\]  

(2)

By changing the amplitude and phase of incident wave \( a_{2,1} \), load reflection coefficient \( \Gamma_{2,1} \) can be shifted in Smith chart. When output \( b_{2,1} \) is constant, setting the amplitude and phase of \( a_{2,1} \) properly, \( \Gamma_{2,1} \) can cover the entire Smith chart [29]. But when the impedance of PA is small, it needs very big reverse power to let \( \Gamma_{2,1} \) cover the whole Smith chart, and it is difficult to realize [30].

Normal PAs’ reflection coefficient cannot be too large, then \( \Gamma_{2,1} \) is limited to a certain range, and the maximum amplitude of \( \Gamma_{2,1} \) is set to \( \Gamma_{2,1}\text{max} \). Then the extraction process of \( K_{n,h,m} \) coefficients is illuminated in Fig. 2.

![Fig. 2. Extraction process of \( K_{n,h,m} \) coefficients.](image)

The amplitude of \( a_{2,1} \) is related to the amplitude of \( b_{2,1} \), which is frequency and power dependent. As the sweeping range of \( |\text{a}_{2,1}| \) is frequency and power dependent, this method can be called dynamic \( a_{2,1} \) sweeping method. \( \Gamma_{2,1}\text{max} \) is set to 0.75 in this letter, then \( \Gamma_{2,1} \) is swept from 0.05 to 0.75, interval 0.1. And the point of \( \Gamma_{2,1} = 0 \) is added to ensure the robustness of simulation at small signals. The phase of \( a_{2,1} \) is swept from 0 to 330 degrees, interval 30 degrees. The behavioral model is taken a total of 97 points on the reflection coefficient Smith chart. Due to the nonlinearity of PA, the reflection coefficients obtained are not regular. However, the dynamic \( a_{2,1} \) sweeping method can still cover most of the target area in Smith chart.

For load-dependent X-parameter, the amplitude and phase of the load reflection coefficient is swept. In this case, the amplitude of \( \Gamma_{2,1} \) is swept from 0 to 0.8, step 0.1, and the phase of \( \Gamma_{2,1} \) is swept from 0 to 330 degrees, step 30 degrees. Load-pull dependent X-parameter is taken a total of 109 points on reflection coefficient chart.
In Fig. 3, the sample points of dynamic $a_{2,1}$ sweeping method and load-dependent X-parameter are compared. Each set of points in the radial direction is the load reflection coefficient obtained by sweeping the amplitude of $a_{2,1}$ when fixing $a_{2,1}$’s phase. The load reflection coefficient of load-dependent X-parameter is evenly distributed, while the maximum value of $f_{2,1}$ in dynamic $a_{2,1}$ sweep method varies from 0.63 to 0.94. For a PA, the output VSWR is generally controlled to be less than 3, which converted to a load reflection coefficient of 0.5 or less. With the above settings, PA’s load reflection coefficient measurement requirements can be met. The result shows that the proposed method do not need a tuner for load impedance adjustment. By using a dynamic $a_{2,1}$ sweeping method, coverage of most of area in Smith chart can be achieved, which can get similar results with load-pull method.

After DUT’s incident and scattered waves are obtained, Eq. (1) can be expressed to Eq. (3). For each amplitude of $a_{1,1}$ and $a_{2,1}$, there are 12 corresponding phases of $a_{2,1}$, so there are 12 sets of data.

$$
\begin{bmatrix}
    p_{1,1} & ... & p_{1,12} \\
    p_{2,1} & ... & p_{2,12} \\
    p_{3,1} & ... & p_{3,12} \\
    p_{4,1} & ... & p_{4,12} \\
    p_{5,1} & ... & p_{5,12} \\
    p_{6,1} & ... & p_{6,12} \\
\end{bmatrix}
= 
\begin{bmatrix}
    K_{1,1} & K_{1,2} & K_{1,1} & K_{1,2} & K_{1,3} & K_{1,4} & K_{1,5} & K_{1,6} & K_{1,7} & K_{1,8} & K_{1,9} & K_{1,10} & K_{1,11} & K_{1,12} \\
    K_{2,1} & K_{2,2} & K_{2,3} & K_{2,4} & K_{2,5} & K_{2,6} & K_{2,7} & K_{2,8} & K_{2,9} & K_{2,10} & K_{2,11} & K_{2,12} \\
    K_{3,1} & K_{3,2} & K_{3,3} & K_{3,4} & K_{3,5} & K_{3,6} & K_{3,7} & K_{3,8} & K_{3,9} & K_{3,10} & K_{3,11} & K_{3,12} \\
    K_{4,1} & K_{4,2} & K_{4,3} & K_{4,4} & K_{4,5} & K_{4,6} & K_{4,7} & K_{4,8} & K_{4,9} & K_{4,10} & K_{4,11} & K_{4,12} \\
    K_{5,1} & K_{5,2} & K_{5,3} & K_{5,4} & K_{5,5} & K_{5,6} & K_{5,7} & K_{5,8} & K_{5,9} & K_{5,10} & K_{5,11} & K_{5,12} \\
    K_{6,1} & K_{6,2} & K_{6,3} & K_{6,4} & K_{6,5} & K_{6,6} & K_{6,7} & K_{6,8} & K_{6,9} & K_{6,10} & K_{6,11} & K_{6,12} \\
\end{bmatrix}
\begin{bmatrix}
    b_{1,1} \\
    b_{2,1} \\
    b_{3,1} \\
    b_{4,1} \\
    b_{5,1} \\
    b_{6,1} \\
\end{bmatrix}
$$

(3)

Use Eq. (4) to stand for Eq. (3)

$$\begin{bmatrix}
    B \\
\end{bmatrix} = \begin{bmatrix}
    K \\
\end{bmatrix} \begin{bmatrix}
    Q \\
\end{bmatrix}$$

(4)

Since there are 12 data sets of matrix $B$, which is larger than the number of unknowns in $K$ matrix, which is 6, least squares method could be used to solve the unknowns. Multiply two sides of the equation by Hermitian transpose of $B$ matrix, Eq.(4) is changed to Eq. (5).

$$\begin{bmatrix}
    B \\
\end{bmatrix}^H \begin{bmatrix}
    B \\
\end{bmatrix} = \begin{bmatrix}
    K \\
\end{bmatrix}^H \begin{bmatrix}
    Q \\
\end{bmatrix} \begin{bmatrix}
    B \\
\end{bmatrix}^H$$

(5)

Finally, $K_{n,h,m}$ matrix could be obtained in Eq.(6). As $K$ matrix is the key factor of the proposed behavioral model, it could be called K-parameter.

$$\begin{bmatrix}
    K \\
\end{bmatrix} = \begin{bmatrix}
    B \\
\end{bmatrix} \begin{bmatrix}
    B \\
\end{bmatrix}^H \begin{bmatrix}
    Q \\
\end{bmatrix} \begin{bmatrix}
    B \\
\end{bmatrix}^{-1}$$

(6)

3. Model Validation

3.1 Comparison with circuit model

A 2-6GHz 3W PA designed based on NP25-00 Gallium Nitride process with Win Semiconductors Corp. is used as circuit model. K-parameter is extracted from this circuit. When input power is swept from -30dBm to 10dBm at 3GHz, the amplitude and phase of the fundamental, second and third harmonics of circuit design and K-parameter are compared in Fig. 4. In both linear and nonlinear regions, the results of K-parameter and circuit match very well.

![Fig. 3. Comparison of sample points in Smith chart of dynamic $a_{2,1}$ sweeping strategy (blue square) and Load-pull dependent X-parameter (red circle), and two validation points (black cross).](image)

![Fig. 4. Output power(a) and phase (b) of PA's circuit (lines) and K-parameter(symbols) in fundamental and harmonics.](image)
Time-domain waveforms are also used for validation. To test the interpolation capability of the behavioral model, reflection coefficient points other than extraction points are selected for the load-dependent X-parameter and K-parameter. The points are marked as Point 1 and Point 2 in Fig. 3, and the reflection coefficients are 0.41+j0.33 and -0.37-j0.14 respectively. The output voltage waveforms are showed in Fig. 6. For point 1, the waveforms for load-dependent X-parameter, behavioral model and circuit simulation results are highly agreed. For point 2 where the nonlinearity is more serious, the harmonic mismatch will be larger. Since the behavioral model and the X-parameter only consider the reflection of the fundamental wave and ignore harmonic reflections, the results have a little discrepancy.

3.2 Comparison with measurement

Experimental measurement results are also provided in order to validate the extraction method and accuracy of K-parameter. The measurement block diagram and measurement setup are illuminated in Figure 7 and Figure 8. A Mini-Circuits ZX60-14012L-S+ amplifier [31] is measured here. The device is operated at 2 GHz and excited by 5dBm signal from Keysight’s NVNA PNA-X N5245B. The travelling waves from DUT’s input and output ports are received by NVNA’s receivers. A 10dB 10W attenuator is used to ensure the DUT’s output power is much lower than driver amplifier’s output power. Two 30dB high power couplers are used to collect the travelling waves for instrument’s receivers. The driver amplifier’s $P_1$ is 27dBm at 2GHz and its working band from 0.1-40GHz with more than 25dB gain. The output incident signal is $\alpha_2$, and its amplitude and phase are controlled by NVNA. The reverse driver amplifier could output about 23dBm power in linear region, and 12dBm power arrived at ZX60’s output port.
Using the proposed dynamic $a_{2,1}$ sweeping method, the incident and the scattered waves are obtained and the $K_{n,h,m}$ coefficients are extracted. Fig. 9 shows the comparisons of measurement and extracted behavioral model’s AM-AM, AM-PM characteristics in fundamental and harmonics, when the input power was swept from -15dBm to 5dBm at 2GHz. The amplitude and phase for the fundamental and second harmonic wave are in good agreement, and the third harmonics are matched well except for input power around -15dBm. As the power of third harmonic is about -70dBm, which below K-parameter extraction system’s dynamic range about -65dBm.

Fig. 9. Output power (a) and phase (b) of amplifier’s measurement(lines) and behavioral model(symbols) in fundamental and harmonics.

To consider the load-pull capability of the behavioral model, an unmatched load is connected to amplifier’s output, and the waveforms of DUT’s output port are recorded. Focus microwaves’ CCMT2620 tuner [32] is connected to a 50ohm load to act as unmatched load and its $S_{11}$ is measured. Then the $S_{11}$ file is imported to simulation software and connected to behavioral model. After simulation, the output waveforms of behavioral model and unmatched load are obtained. Fixing tuner’s Gamma to 0.3 and changing its phase to 25 and 200 degrees. Fig. 10 shows that behavioral model could reflect the change of different load when $\Gamma_{2,1}$ is less than 0.5, and the response is agree with measurement results.

Fig.10. Output power (a) and phase (b) of amplifier’s measurement(lines) and behavioral model(symbols) when connected to different unmatched loads.

Using extracted K-parameter, load-pull simulation could be done. Fig. 11 illuminates constant power delivery contours simulated using K-parameter. As DUT’s inverse incident power is half of DUT’s output power, the contours inside $\Gamma_{2,1}=0.5$ is shown.

Fig. 11. Power delivery contours simulated using K-parameter.

4. Conclusion

A simplified extraction method for power amplifier has been proposed and validated through nonlinear large signal simulation and measurement. The fundamental output incident signal acts as both disturbance signal and active load-pull driver signal. And using dynamic $a_{2,1}$ sweeping method, the model can reflect the influence of different load
impedances, and has interpolation capability. This letter also proposed a novel model extraction method that covers most areas of the Smith Chart without using a tuner while ensuring lower measurement costs.

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