Recent Development of Cardiff Behavioural Model: Including DC Supply Voltage Into the Model's Formulation

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***Abstract*—This paper includes the recent development of Cardiff model's formulation to include the DC bias voltages. The new DC-dependent Cardiff model's formulation is capable of accurately interpolating the load-pull data with respect to DC bias; hence, significantly reducing the density of load-pull data over a wide range of DC bias points. For the case presented, interpolation of load-pull data has resulted in more than 90% reduction in the density of the load-pull data required to generate a nonlinear behavioural model over a wide range of DC bias points.**

I. Introduction

Advancement in large-signal and waveform measurement systems [1], [2], has created an opportunity for direct utilisation of measurement data (specifically load-pull measurement) into the computer-aided design (CAD) environment [3]. However, the generality requirement of advanced radio-frequency power amplifier (RFPA) designs demands load-pull data under various variables such as frequency, input power, and DC bias voltage which can be very time-consuming. Therefore, it is critical to adopt a strategy to reduce the measurement intensity and in doing so, reduce measurement time. One approach to reducing the density of the required load-pull data is to use an accurate and reliable nonlinear behavioral model to interpolate the data.

Current industry-leading nonlinear behavioural models are Cardiff University's Cardiff behavioural model [4] and Keysight's X-parameters [5]. Regarding the Cardiff model, to enhance its generality, variables such as frequency, transistor size, input power, etc. have been previously included into its mathematical formulation [6], [7]. In terms of DC bias, however, in the conventional formulation of Cardiff model [8] (and also X-parameters [9]) the DC bias voltages are treated as independent variables; hence, load-pull measurements at each DC bias voltage were required to generate a bias-dependent model. The CAD tools could be allowed perform simple interpolation.

This paper provides a summary of our recent works in [10] and [11], which were dedicated to develop a new mathematical formulation capable of predicting the device behaviour under various DC bias conditions.

II. Cardiff Model

A. Cardiff model definition

Mathematical development of Cardiff behavioural model was based on the general mixing theory to account for the fact that when multiple CW harmonically related stimuli are injected into a multi-port nonlinear system, they interact ('mix') [12]. The polynomial expansion of the model is formed around a limited operational domain about a large signal operating point (LSOP), for example at a fixed input RF input drive level, frequency, and DC bias point,

Equation (1) shows the general mathematical formulation of the Cardiff model, in the 'A' and 'B' domain, for fundamental load-pull only at a fixed input drive, and DC bias condition [8]. The 'p' is the port index and 'h' is the harmonic index, referenced to the fundamental frequency 'f_0', The parameters 'm' and 'n' denote the coefficient related stimulus phasor '$A_{2,1}$' magnitude and phase exponents, respectively. The 'm' and 'n' are related as '$m = |n|+2r$' where 'r' is the magnitude indexing term.

$$B_{p,h} = (\angle A_{1,1})^h \cdot \sum_{r=0}^{1} \sum_{n=n_{min}}^{n_{max}} \ldots, K_{p,h,m,n} \cdot |A_{2,1}|^m \cdot \left(\angle \frac{A_{2,1}}{A_{1,1}}\right)^n \quad (1)$$

where,

$$\begin{cases} n_{\min} = -(w - h/2 - r) \\ n_{\max} = h + (w - h/2 - r), \end{cases}$$

and for DC current ($h = 0$) the term "$B_{2,0} \triangleq I_{2,0}$".

As the DC bias voltage is treated as a lookup indexing parameter, the model has no interpolation and/or extrapolation capability relating to the DC supply voltage variation. Therefore, to generate a behavioural model capable of predicting the device's response under various DC bias conditions, load-pull data at all the desired bias points were required.

B. Including the DC voltage variation into the model

To include both RF and DC bias voltages (v^{rf} and V^{DC}) into the Cardiff model formulation, a general mixing equation was considered as:

$$I = \sum_{w=0}^{w=order} \sum_{u=0}^{u=w} C_{u,(w-u)}, \ldots, \left(V_{gs}^{DC} + v_{gs}^{RF}\right)^u \left(V_{ds}^{DC} + v_{ds}^{RF}\right)^{(w-u)}. \quad (2)$$

Referencing to general expression in (2), the model coefficients '$C_{u,(w-u)}$' are used to relate the device's current response 'I' to both RF and DC voltage (v^{rf} and V^{DC}). After expanding this general mixing equation, and separating out the RF and DC stimulus terms, a new "DC-dependent" mathematical formulation for the Cardiff model was developed (3).

$$B_{p,h} = (\angle A_{1,1})^{h} \sum_{r=0}^{1} \sum_{n=n_{min}}^{n_{max}} ,$$
$$\ldots, \left\{ \sum_{u=0}^{u=u_{max}} \sum_{v=u}^{v=v_{max}} L_{p,h,m,n,u,(v-u)} \left(V_{gs}^{DC}\right)^{u} \left(V_{ds}^{DC}\right)^{(v-u)} \right\},$$
$$\ldots, |A_{2,1}|^{m} \left(\angle \frac{A_{2,1}}{A_{1,1}}\right)^{n}. \quad (3)$$

Where '$L_{p,h,m,n,u,(v-u)}$' is the new model coefficient which is independent of the DC bias voltage.

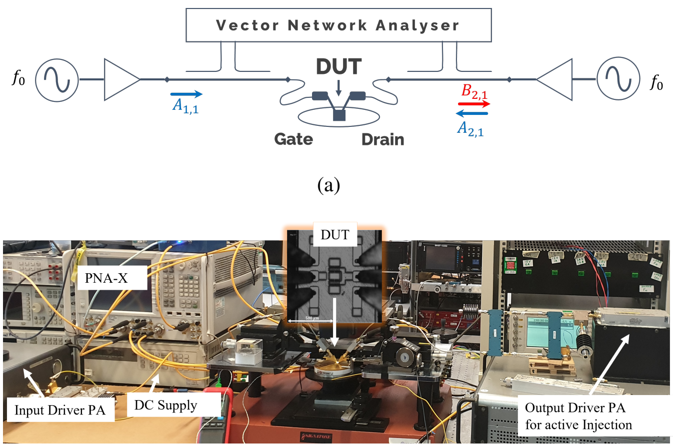
Note, from a physics basis, it is logical to describe the device behavior in the admittance domain (current response as a function stimulus voltage). However, as RF systems measure incident 'A' and reflected 'B' travelling waves, it is common to define the device behaviour in the travelling-wave domain (A,B domain).

Referencing to (3), to use the model, the value of the DC mixing orders (u_{max} and v_{max}) were needed to be identified. Our study in [10] identifies the linear relationship between the convectional Cardiff model coefficients and the 'V_{gs}^{DC}' variation ($u_{max} = 1$). The relationship between model coefficients and 'V_{ds}^{DC}' variation was investigated in [11], where a 3rd order polynomial was determined empirically ($v_{max} = 3$).

III. Verification

A. Measurement strategy

The measurements were conducted statically using continuous wave (CW) excitation at fundamental frequency of 3.5 GHz. For this experiment, only fundamental load-pull measurements were conducted, and harmonic frequencies were terminated at the system impedance. Fig. 1 shows (a) the block diagram, and (b) the photograph of the active load-pull measurement system used for this experiment.



(a)

(b)

Fig. 1. Real-time, active load-pull system (a) Block diagram, and (b) photograph of the system at CHFE, Cardiff University.

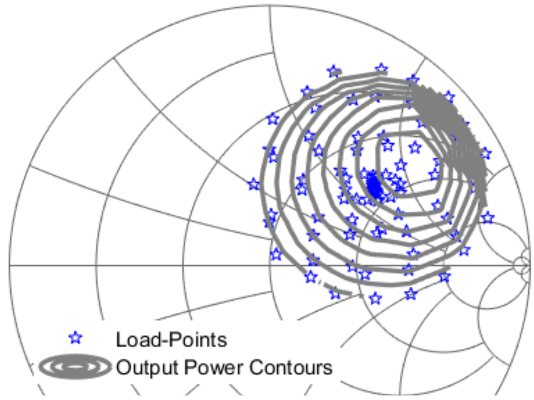


Fig. 2. Load-pull measurement grid with 91 load points. The load-pull measurement was performed under a V_{ds}^{DC} sweep from 20 to 50 V with 3 V step at various V_{gs}^{DC} conditions from -3.0 V to -2.0 V with 0.1 V step. Load-pull grid are selected in a way to capture the optimum load points over all V_{ds}^{DC} voltages. The depicted output contours are at $V_{gs}^{DC} = -2.5\,V$ and $V_{ds}^{DC} = 35\,V$ with a maximum of 32.3 dBm and 0.5 dB step.

The device under test (DUT) was a 4 W GaN-on-SiC from Ampleon, which its V_{ds}^{DC} was swept from 20 V to 50 V with the step of 3 V at various V_{gs}^{DC}, from -3.0 V to -2.0 V with 0.1 V step. At each bias point 91 load points measured using the grid shown in Fig. 2.

B. Normalised Mean Squared Error

The normalised mean squared error (NMSE) is a figure of merit which is used to quantify the deviation of the modelled data from actual measured data. In an ideal case (perfect match between the measured and modelled data), the NMSE value is equal to zero. The definition of NMSE is illustrated in (4) [13].

$$NMSE = \frac{\sum_i |B_{21}{}^{meas} - B_{21}{}^{model}|^2}{\sum_i |B_{21}{}^{meas}|^2} \quad (4)$$

To verify the inclusion of both V_{gs}^{DC} and V_{ds}^{DC}, the model was extracted using a subset of bias points (V_{ds}^{DC}= 20, 29, 41, 50 V and V_{gs}^{DC}=-2.0, -2.5, -3.0 V) and validated on the full set of measurement data. Fig. 3 shows the NMSE for $B_{2,1}$.

As shown in Fig. 3 , the new Cardiff model formulation (3) is capable to accurately predict the load-pull data with NMSE value of better than -39.5 dB across all the datasets. In terms of percentage, there is only 1% deviation between the modelled and measured data.

Note, in this example, the pinch-off voltage is at $V_{gs}^{DC} = -2.7\,$V and load-pull data has been successfully modelled across class AB and class C bias conditions. Fig. 4 depicts a comparison between the measured and interpolated output power contours and the efficiency contour at $V_{ds}^{DC} = 23\,$V and $V_{gs}^{DC} = -2.3\,$V (DC bias condition with the lowest accuracy in Fig. 3).

In this example, using the load-pull data of only 12 bias points (4 V_{ds}^{DC} points and 3 V_{gs}^{DC} points), load-pull data of 121 bias points (11 V_{ds}^{DC} points and 11 V_{gs}^{DC} points) were predicted accurately. Compared to the conventional Cardiff model formulation, to generate the same model, the total

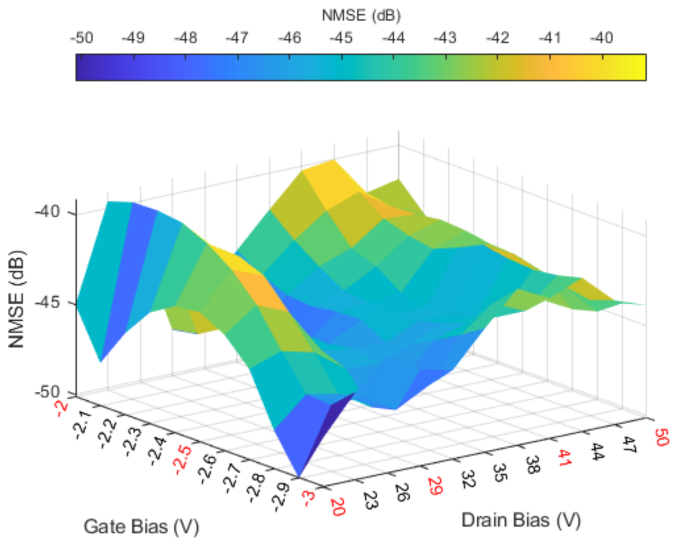
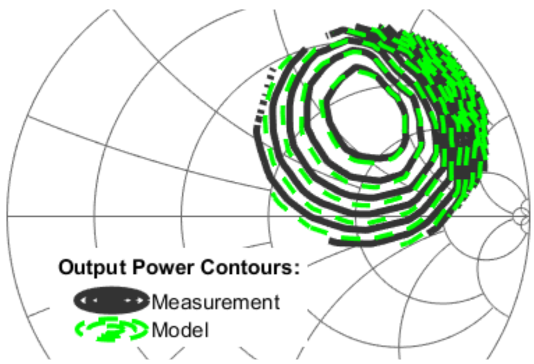
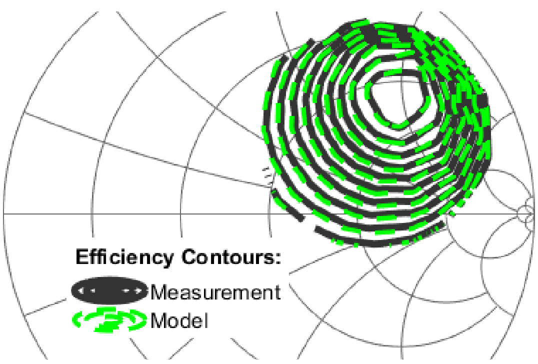


Fig. 3. NMSE (dB) of $B_{2,1}$ at different DC bias conditions. The NMSE is better than -39.5 dB across all the DC bias conditions. The pinch-off voltage is at $V_{gs}^{DC} = -2.7\ V$. Only the DC data points highlighted in **'red'** were used to generate the model, and the data at all the other DC bias voltages are interpolated.



(a)



(b)

Fig. 4. Comparison of measured and interpolated load-pull power contours (0.5 dBm step from maximum of 31.3 dBm) and efficiency contours (0.5% step from a maximum of 61.8%) at $V_{ds}^{DC} = 23\,V$ and $V_{gs}^{DC} = -2.3\,V$.

number of required load-pull data points have significantly reduced from 11011 points (91 load points at 121 DC bias points) to only 1092 points. That is, in this case, more than a 90% reduction in the load-pull measurement's density with respect to the DC bias points.

IV. Conclusion

In this paper, a summary of the recent work on Cardiff behavioural model to include both gate and drain bias variations has been presented. The model accuracy in the interpolation domain has been verified, using measurement data of a real device at different DC bias points, and the NMSE is below -39 dB for all data points. The work shows that the dataset needed to accurately model this measurement space can be reduced by 90% while still maintaining good accuracy.

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