A New Assessment of pHEMT Models by Comparing Relative Errors of Drain Current and Its Derivatives Up to the Third Order

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Abstract—At present, there are relatively more precise pHEMT models available for computer-assisted design, and they are frequently compared to each other. However, such comparisons are mostly based on absolute errors of drain-current equations and their derivatives. In a paper, a novel method is suggested based on relative root-mean-square errors of both drain current and its derivatives up to the third order. Moreover, the relative errors are then relativized to the best model in each category to further clarify obtained accuracies of the drain current and its derivatives. Furthermore, one older and two newly suggested models are also included in the comparison with the traditionally accurate Ahmed, TOM2 and Materka ones. The assessment is performed using measured characteristics of a 110 GHz pHEMT. Finally, a usability of the models of the higher-order derivatives is illustrated using an IP3 computation/measurement of a multi-constellation receiver for a satellite navigation with ATF-54143.

I. INTRODUCTION

Finding and identifying a convenient pHEMT model for radio electronics is not a simple problem. Probably the most challenging tasks are simulations of a (critical) mixing $2f_2-f_1$ product because this needs credible 3rd-order derivatives of the model functions. Generally, traditional simpler models like Curtice, Statz, and TOM [1] are used as well as more accurate ones as TOM2 [2], Ahmed [3], Parker-Skellern [4], or Materka [5]. Besides that, we also suggested some modified and novel models [6], [7]. All these models included our one were often compared as shown in [3], e.g. However, the most of the comparisons are based on absolute values especially for the higher-order derivatives. Hence, we suggest a novel way for the comparison based on ratios of relative errors of the models.

II. COMPLETE EQUATIONS OF OUR SUGGESTED NOVEL MODELS

A shortened description of the suggested TANH and XEXP models was shown in [7]. A complete equation is defined as

$$i_{DS} = \begin{cases} g_m v_{DS} & \text{for } v_{GS} - (V_{T0} - \gamma v_{DS}) \leq 0 \land N_G + N_D v_{DS} = 0, \\ g_m v_{DS} + \beta v_G^* (1 + \alpha v_{DS}) \tanh(\alpha v_{DS}) & \text{otherwise,} \end{cases}$$

and the two principally novel formulae have been suggested for the $V_G^*$ factor to characterize a transconductance dependence ($V_G^*$ creates a new layer in the hierarchy of model equations):

$$V_G^* = \begin{cases} V_{TS} \ln \left( \frac{v_G}{V_{TS}} \right) & \text{for TANH}, \\ V_{TS} \left[ e - \left( 1 + \frac{v_G}{V_{TS}} \right)^{-1} \exp \left( 1 - \frac{v_G}{V_{TS}} \right) \right] & \text{for XEXP}. \end{cases}$$

The transconductance is newly estimated as $\tanh \left( \frac{V_G}{V_{TS}} \right)$ for the TANH model, and by integrating the term $\frac{V_G}{V_{TS}} \exp \left( 1 - \frac{V_G}{V_{TS}} \right)$ for the XEXP model. $V_{TS}$ (voltage of transconductance slope) is a new model parameter, and for the $V_G$ factor, the formulae were slightly simplified ($V_G^*$) from those in the TOM2 model:

$$V_G = V_{ST}^* \ln \left[ e^{\frac{V_{GS} - (V_{T0} - \gamma v_{DS})}{V_{TS}^*}} + 1 \right], V_{ST}^* = 2(N_G + N_D v_{DS}) \frac{kT}{q}.$$  

All the other model parameters are defined in [1], and formulae for capacitances were used in the same way as those in [2].

III. COMPARISON OF RELATIVE ROOT-MEAN-SQUARE ERRORS

First, we computed absolute errors for all the tested models with typical results for drain current and its derivatives shown in Figs. 2 and 3. However, unlike in the majority of other papers, we also computed relative errors not only for the drain current as usual, but also for all its derivatives. Furthermore, we relativized all these errors to the one of a model with the smallest error. All the models that have this error more than ten times greater than that of the best model in some category of the derivatives were excluded (i.e., Curtice, Statz, and TOM), and the final results of this comparison are shown in Table I.

| Model | $i_D$ | $\frac{\partial i_D}{\partial v_{DS}}$ | $\frac{\partial^2 i_D}{\partial v_{DS}^2}$ | $\frac{\partial^3 i_D}{\partial v_{DS}^3}$ | $\frac{\partial i_D}{\partial V_{GS}}$ | $\frac{\partial^2 i_D}{\partial V_{GS}^2}$ | $\frac{\partial^3 i_D}{\partial V_{GS}^3}$ |
|------|------|-----------------|-----------------|-----------------|----------------|-----------------|-----------------|
| Ahmed | 4.2  | 2.51            | 1.0             | 1.24            | 4.69          | 1.0             | 1.0             |
| Dobeš | 4.49 | 6.49            | 1.29           | 1.13            | 1.6           | 7.6             | 3.35            |
| TOM2  | 1.66 | 4.38            | 1.99           | 1.85            | 2.08          | 1.9             | 7.5             |
| Materka | 4.21 | 3.5             | 1.52           | 1.2             | 1.45          | 5.54            | 3.13            |
| TANH  | 1    | 2.51            | 1.12           | 1.15            | 1.11          | 1               | 1.02            |
| XEXP  | 1.01 | 1.27            | 1.2            | 1               | 4.46          | 1               | 1               |

The transconductance is $\tanh \left( \frac{V_G}{V_{TS}} \right)$ for the TANH model, and by integrating the term $\frac{V_G}{V_{TS}} \exp \left( 1 - \frac{V_G}{V_{TS}} \right)$ for the XEXP model. $V_{TS}$ (voltage of transconductance slope) is a new model parameter, and for the $V_G$ factor, the formulae were slightly simplified ($V_G^*$) from those in the TOM2 model:

$$V_G = V_{ST}^* \ln \left[ e \frac{V_{GS} - (V_{T0} - \gamma v_{DS})}{V_{TS}^*} + 1 \right], V_{ST}^* = 2(N_G + N_D v_{DS}) \frac{kT}{q}.$$  

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IV. CHECKING THE MODEL BY THIRD-ORDER INTERCEPT POINT

A good idea of checking the 3rd-order derivatives is comparing computed/measured IP3 of an RF circuit with pHEMT. For this purpose, we have used a satellite-navigation receiver in Fig. 1 with ATF-54143 [10]. The obtained computed/measured IP3 points in Fig. 4 have shown a quite acceptable agreement.

V. CONCLUSIONS

A new method of relative error comparisons gave meaningful score of the models, and the IP3 analysis showed a viability.
Fig. 1. Schematic of a low-noise antenna preamplifier for the multi-constellation GPS/Galileo/GLONASS/Compass receiver, which has been used for comparing a measurement/simulation IP$_3$. The parameters shown in red indicate the values before/after the multi-objective optimization, searching a NF/GT trade-off [8].

Fig. 2. Typical errors: Ahmed model used for 110 GHz 0.25 μm pHEMT [9].

Fig. 3. Modeling of the 3rd-order derivative $\frac{\partial^3 I_D}{\partial V_{GS}^3}$ by the TANH model. (This derivative is important for accurate estimation of the $2f_2-f_1$ mixer product.) Measurement (marks)/simulation (lines) values differ for greater values of $V_{DS}$.

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Fig. 4. Computation (blue and red) and measurement (gray) of the LNA IP$_3$. Selected frequencies $f_2$ and $f_1$ were 1576 and 1575 MHz, respectively, and signal levels were the same. (Let’s note the typical pHEMT S-shape of IM3.)

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