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A NEW ACCURATE VOLTERRA-BASED MODEL FOR BEHAVIORAL MODELING AND DIGITAL PREDISTORTION OF RF POWER AMPLIFIERS

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Abstract—A new accurate Volterra-based model is introduced for behavioral modeling and digital predistortion (DPD) of power amplifiers (PAs). This model extends the GMP model with specific cross terms, and these augmented terms significantly increase the model's performance. The proposed model's performance is assessed using a LDMOS Doherty PA driven by two modulated signals (a 4-carrier WCDMA signal and a single carrier 16QAM signal). The experimental results in both behavioral modeling and DPD applications demonstrate that the proposed model outperforms the hybrid memory polynomial-envelope memory polynomial (HME) model and generalized memory polynomial (GMP) model. Compared with the HME model, the proposed model shows an average normalized mean square error (NMSE) improvement of 2.2 dB in the behavioral modeling, average adjacent channel power ratio (ACPR) improvement of 2.8/2.5 dB in the DPD application, and 20% reduction in the number of coefficients. In comparison with the GMP model, the proposed model achieves higher model accuracy and better DPD performance, but reduces approximately 40% of coefficients.

1. INTRODUCTION

Radio frequency (RF) power amplifiers (PAs) are one of the most important components in wireless communication systems, but they are also the major source of nonlinearity. Many linearizing techniques are used in the power amplifiers [1–3]. Compared with the analog linearizing methods, processing the base band signals in the digital area

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has many advantages such as high flexibility, applicability, and easy to realize the adaptive processing. Therefore, it has great potential to research and develop the digital predistortion (DPD) technique [1].

One of the main challenges in developing effective DPD technique is to find a way to capture the nonlinear distortion and memory effects of the PA using an accurate behavioral model. Volterra series can accurately describe the nonlinear system, but it involves a great number of coefficients [4–8]. Several behavioral models have been proposed for PAs and transmitters, such as the Memory Polynomial (MP) model, Envelope Memory Polynomial (EMP) model, HME model, and GMP model [9–13]. The MP model contains the diagonal terms of Volterra series, while the EMP model is composed of cross items between the signal and lagging exponentiated envelope terms, and the two models combine together to form the HME model. It has been confirmed that the HME model outperforms the MP model and EMP model. The GMP model combines the MP model with cross terms between the signal and lagging and/or leading exponentiated envelope terms. It can be seen that the cross terms introduced by the EMP model are special cases of the GMP model's lagging cross terms. Though several behavioral models have been proposed and applied to DPD, the study on modeling technique is still far from being mature since accurately characterizing RF PAs becomes more and more difficult as wireless communication systems migrate to higher frequencies, higher speeds, and wider bandwidths.

In this paper, we present a new accurate Volterra-based behavioral model for behavioral modeling and DPD of RF PAs. In fact, the proposed model can be applied to nonlinearity compensation in a variety of dynamic nonlinear systems used in industrial electronic applications. Since this model has linear dependence on the coefficients, the estimation of these coefficients can be achieved by any least-squares (LS) type of algorithm [13]. In addition, the number of coefficients can be controlled through a proper choice of model dimensions. The model's performance in behavioral modeling and DPD applications is assessed using a LDMOS Doherty PA, and two test signals (a 4-carrier WCDMA signal and a single carrier 16QAM signal) are used for verifications. This paper also presents a thorough comparison between the proposed model and the HME model, as well as the GMP model. Normalized mean square error (NMSE) and error power spectral density (EPSD) are considered to evaluate the model accuracy while adjacent channel power ratio (ACPR) is used to assess the DPD application [14–17]. The computational complexity is characterized by the number of coefficients required for each model [17]. The comparison results fully illustrate that the new model outperforms the other two models with the least number of coefficients in both behavioral modeling and DPD applications.

2. VOLTERRA-BASED BEHAVIORAL MODELS

The MP model takes the diagonal terms of Volterra series, and its mathematical formulation is given by [9, 10]

$$y_{\mathrm{MP}}(n) = \sum_{k=1}^{K} \sum_{q=0}^{Q} a_{kq} x(n-q) \left| x(n-q) \right|^{k-1} \tag{1}$$

where $x(n)$ and $y_{\mathrm{MP}}(n)$ are the input and output waveforms of the MP model, respectively. Q, K and a_{kq} are the memory depth, nonlinearity order, and model coefficients, respectively.

When the complex gain of the PA is only a function of the magnitude of the input signal, EMP can be used, and the corresponding formulation is [11]

$$y_{\mathrm{EMP}}(n) = \sum_{k=1}^{K} \sum_{q=0}^{Q} a_{kq} x(n) \left| x(n-q) \right|^{k-1} \tag{2}$$

where $x(n)$ and $y_{\mathrm{EMP}}(n)$ are the EMP model input and output waveforms, respectively. Q, K and a_{kq} are the memory depth, the nonlinearity order, and the model coefficients, respectively. Compared with the MP model, the EMP model has an easier structure.

To combine the benefits of the two models mentioned above, the HME model is proposed in [12]. It is demonstrated that the HME model achieves better modeling accuracy than each sub-model. The analytical formulation of the HME model is given by

$$\begin{aligned} y_{\mathrm{HME}}(n) = & \sum_{k=1}^{K_a} \sum_{q=0}^{Q_a} a_{kq} x(n-q) \left| x(n-q) \right|^{k-1} \\ & + \sum_{k=1}^{K_b} \sum_{q=0}^{Q_b} b_{kq} x(n) \left| x(n-q) \right|^{k-1} \end{aligned} \tag{3}$$

where $x(n)$ and $y_{\mathrm{HME}}(n)$ are the input and output waveforms of the HME model, respectively. K_a, Q_a and a_{kq} are the nonlinearity order, memory depth, and model coefficients of the MP sub-model, respectively. Equivalently, K_b, Q_b and b_{kq} are the nonlinearity order, memory depth, and model coefficients of the EMP sub-model, respectively.

In the GMP model [13], the estimated output waveform is related to the input waveform by

$$\begin{aligned} y_{\mathrm{GMP}}(n) \;=\; & \sum_{k=1}^{K_a}\sum_{q=0}^{Q_a} a_{kq}x(n-q)\left|x(n-q)\right|^{k-1} \\ & +\sum_{k=2}^{K_b}\sum_{q=0}^{Q_b}\sum_{l=1}^{L_b} b_{kql}x(n-q)\left|x(n-q-l)\right|^{k-1} \\ & +\sum_{k=2}^{K_c}\sum_{q=0}^{Q_c}\sum_{l=1}^{L_c} c_{kql}x(n-q)\left|x(n-q+l)\right|^{k-1} \qquad (4) \end{aligned}$$

where $x(n)$ and $y_{\mathrm{GMP}}(n)$ are the input and estimated output waveforms of the GMP model, respectively. K_a, Q_a and a_{kq} are the nonlinearity order, memory depth, and coefficients of the aligned terms between signal and its exponentiated envelope, respectively. K_b, Q_b, L_b and b_{kql} are the nonlinearity order, memory depth, lagging cross terms index, and coefficients of the signal and lagging exponentiated envelope terms, respectively. K_c, Q_c, L_c and c_{kql} are the nonlinearity order, memory depth, leading cross terms index, and coefficients of the signal and leading exponentiated envelope terms, respectively.

Actually, for the behavioral models mentioned above, it is reasonable to consider only odd-order nonlinearities because the effects from even order kernels can be omitted in a band-limited modulation system [5].

3. DISCRIPTION OF THE NEW VOLTERRA-BASED MODEL

Discrete-time finite-memory complex baseband Volterra series can be used to describe a nonlinear PA of a wireless communication system, the mathematical formulation is given by [8]

$$y(n) = \sum_{\substack{k=1 \\ k-odd}}^{K} \sum_{q_k=0}^{Q_k} h_k(q_k)x(n-q_1) \prod_{m=1}^{(k-1)/2} x(n-q_{2m})x^*(n-q_{2m+1}) \quad (5)$$

where the first summation is restricted to odd values of k; $x(n)$ and $y(n)$ represent the input and output complex envelope samples of PA; $h_k(q_k)$ represents the discrete-time Volterra kernels of order k; q_k is composed of the integer-valued delays, $q_k = 0, \ldots, Q_k$ for all $k = 1, 3, \ldots, K$. Here we consider decaying memory with the same finite length $Q_k = Q$ for all order k.

The Volterra series model provides a general way to describe the nonlinear system, but the number of coefficients to be estimated increases exponentially with the degree of nonlinearity and memory depth of the system. The complexity of the Volterra series model is revealed in the fact that the kernels $h_k(q_k)$ form an k-dimensional grid defined by the discrete delays in each axis of the multidimensional space $q_1, q_2, \ldots, q_k$. Therefore, it is desirable to reduce the number of these delays [7].

Firstly, consider the case that input samples are all at the same time instant, i.e., $q_1 = q_2 = \ldots = q_k = q$, thereby generating a two-dimension (2-D) array from (5). Actually, this is the so-called MP model and it can be written as

$$y_{2-\mathrm{D}}(n) = \sum_{\substack{k=1 \\ k-odd}}^{K} \sum_{q=0}^{Q} h_{kq} x(n-q) \left| x(n-q) \right|^{k-1} \tag{6}$$

Then relax the restriction condition and consider another case that just one time delay distinguishes itself from the others. Assuming that the special time delay is q, the corresponding signal is a x term, while the others are all equal to $q - l$ $(l \geq 1)$. Then the first 3-D array is generated from (5) and it can be expressed as

$$y_{3-\mathrm{D},1}(n) = \sum_{\substack{k=1 \\ k-odd}}^{K} \sum_{q=0}^{Q} \sum_{l=1}^{L} h_{kql}^{(1)} x(n-q) \left| x(n-q-l) \right|^{k-1} \tag{7}$$

When $q = 0$, it can be seen that (7) degenerates into an EMP model, as described in (2). Furthermore, the degraded (7) and (6) constitute the HME model.

If the other time delays are all equal to $q + l$ $(l \geq 1)$, we can formulate the second 3-D array as

$$y_{3-\mathrm{D},2}(n) = \sum_{\substack{k=1 \\ k-odd}}^{K} \sum_{q=0}^{Q} \sum_{l=1}^{L} h_{kql}^{(2)} x(n-q) \left| x(n-q+l) \right|^{k-1} \tag{8}$$

It can be seen that Equation (6) together with (7) and (8) lead to the GMP model. Similarly, if the signal with the special time delay is a x^* term, another two 3-D arrays are achieved

$$y_{3-\mathrm{D},3}(n) = \sum_{\substack{k=3 \\ k-odd}}^{K} \sum_{q=0}^{Q} \sum_{l=1}^{L} h_{kql}^{(3)} x^*(n-q) x^2(n-q-l) \left| x(n-q-l) \right|^{k-3} \tag{9}$$

and

$$y_{3-\mathrm{D},4}(n) = \sum_{\substack{k=3\\k-odd}}^{K} \sum_{q=0}^{Q} \sum_{l=1}^{L} h_{kql}^{(4)} x^*(n-q) x^2(n-q+l) \left|x(n-q+l)\right|^{k-3} \tag{10}$$

It is obvious that if we continue this process, more items will be produced, which is not feasible for practical application. Thus we put a termination to the process, the resulting outputs $y_{2-\mathrm{D}}(n)$, $y_{3-\mathrm{D},1}(n)$, $y_{3-\mathrm{D},2}(n)$, $y_{3-\mathrm{D},3}(n)$ and $y_{3-\mathrm{D},4}(n)$ are additively combined to construct the overall output signal of the new Volterra-based model, and its analytical formulation is given by

$$y(n) = y_{2-\mathrm{D}}(n) + \sum_{m=1}^{4} y_{3-\mathrm{D,m}}(n) \tag{11}$$

where $y(n)$ is the output waveforms of the new pruned Volterra series model.

In most real PAs, the static nonlinearities and low-order dynamics are the dominant sources of the distortions induced by the PA [12]. In addition, the GMP model (Equation (6) together with (7), (8)) has proven effective for predistortion of actual PAs [13, 17]. Equations (9) and (10) can be seen as supplements to the GMP model, so it is reasonable to just retain the 3rd-order dynamics of Equations (9) and (10) to reduce the model complexity. Furthermore, there is no need to take the same model dimensions for all the arrays. They can be controlled separately, which leads to a reasonable total number of coefficients while maintaining acceptable performance. Finally, Equation (11) is further simplified as follows

$$\begin{aligned} y(n) \; = \; & \sum_{\substack{k=1\\k-odd}}^{K_a} \sum_{q=0}^{Q_a} a_{kq} x(n-q) \left|x(n-q)\right|^{k-1} \\ & + \sum_{\substack{k=3\\k-odd}}^{K_b} \sum_{q=0}^{Q_b} \sum_{l=1}^{L_b} b_{kql} x(n-q) \left|x(n-q-l)\right|^{k-1} \\ & + \sum_{\substack{k=3\\k-odd}}^{K_c} \sum_{q=0}^{Q_c} \sum_{l=1}^{L_c} c_{kql} x(n-q) \left|x(n-q+l)\right|^{k-1} \\ & + \sum_{q=0}^{Q_d} \sum_{l=1}^{L_d} d_{ql} x^*(n-q) x^2(n-q-l) \end{aligned}$$

$$+\sum_{q=0}^{Q_e}\sum_{l=1}^{L_e} e_{ql}x^*(n-q)x^2(n-q+l) \tag{12}$$

where K_a, K_b and K_c are the nonlinearity order of the first three arrays, respectively. Q_a, Q_b, Q_c, Q_d and Q_e are the memory depth of the five arrays, respectively. L_b, L_c, L_d and L_e are the corresponding lagging or leading cross terms index of the last four arrays, respectively. a_{kq}, b_{kql}, c_{kql}, d_{ql} and e_{ql} are the coefficients of the proposed model. Like those of the GMP model, the coefficients of the proposed model appear in linear form. Therefore, the coefficients can be simply and robustly estimated using any least-squares type of algorithm. This has favorable implications for algorithm stability and computational complexity [13].

Apparently, the new Volterra-based model extends the GMP model with specific cross terms. Compared with the GMP model, the proposed model dimensions are defined by four more variables, but the augmented terms further increase the accuracy of the model. In addition, the model's complexity can be controlled through the proper choice of the model dimensions.

4. THE EXPERIMENTAL RESULTS AND DISCUSSION

In order to validate the proposed behavioral modeling technique in a real system, a highly nonlinear 80 W LDMOS Doherty PA ($V_{ds} = 28$ V, $V_{gs} = 5.6$ V) was tested. This PA was operated at 1.96 GHz and excited by a 4-carrier WCDMA signal (PAPR = 8.7 dB) and a 15 MHz data ratesingle carrier 16QAM signal (PAPR = 6.2 dB). Fig. 1 shows the test bench set-up.

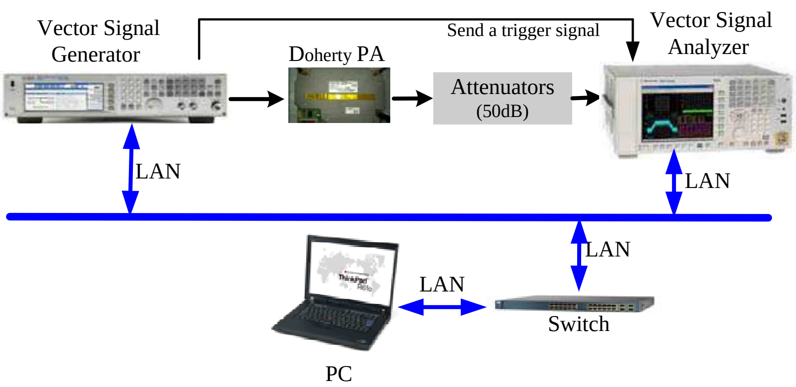

Figure 1. Experiment test bench.

This experimental setup was composed of a LDMOS Doherty PA, a vector signal generator (N5182A), a vector signal analyzer (VSA), and a computer. The computer was used to download signals into the N5182A that drove the PA with the RF input signals. The output signals of the PA was attenuated and then down-converted and demodulated within the VSA. MATLAB software was then applied to behavioral modeling and DPD. 4000 samples of the input and output waveforms were used for model identification employing the LS (Least Squares) algorithm [17]. For comparison,we also implemented the HME model, the GMP model and they are represented as Model M1 and Model M2 respectively in the following measure results. The proposed model as shown in (12) is called Model M3.

4.1. Model Accuracy Evaluation

For each test signal, the HME model, GMP model, and the proposed model were all identified. Two assessments were considered to evaluate the model accuracy: NMSE in the time domain and EPSD in the frequency domain [14–17].

The MP sub-model dimensions are estimated using a general sweep method [17]. The memory depth is swept from 0 to 5, and the nonlinearity order is swept from 1 to 13. Fig. 2 shows the NMSE values versus the memory depth K_a and nonlinearity order Q_a obtained for the 4-carrier WCDMA signal. Accordingly, the dimensions of the MP sub-model are set to $K_a = 9$ and $Q_a = 3$.

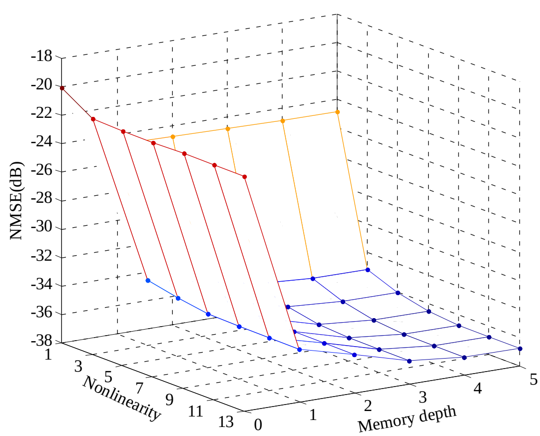

Figure 2. NMSE values versus the nonlinearity order and memory depth of the MP sub-model.

For the sake of reducing model complexity, the lagging or leading cross terms indexes (L_b, L_c, L_d and L_e) and the memory depths of the added cross terms (Q_d and Q_e) are set to 1. In order to avoid accidental results, K_b/K_c and Q_b/Q_c are set to different values and the corresponding NMSEs are summarized in Table 1.

As highlighted in Table 1, compared with the HME model, the proposed model shows a NMSE improvement of 1.6 dB with 80% coefficients. The GMP model performance in terms of NMSE does not exceed −37 dB even if the number of parameters is increased far above the total number of parameters that are used for the proposed model to achieve an NMSE that exceeds −37.18 dB. In this case, the EPSD plots along with the original PA output spectra are shown in Fig. 3. This figure makes it clear that the proposed model also achieves the best performance in the frequency domain.

These models were also identified for the single carrier 16QAM signal, model dimensions were set to different values as used for the 4-carrier WCDMA signal. Fig. 4 shows the comparison of the three models in terms of the NMSE as a function of the number of coefficients. This figure clearly illustrates the advantage of the proposed model in terms of the NMSE. In the case that stressed in Fig. 4, the EPSD plots along with the original PA output spectra are shown in Fig. 5. Obviously, the proposed model achieves the lowest error in the frequency domain.

According to the calculated results in terms of NMSE, EPSD

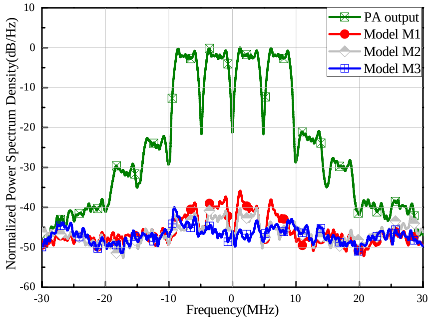

Figure 3. EPSD plots for the 4-carrier WCDMA signals test.

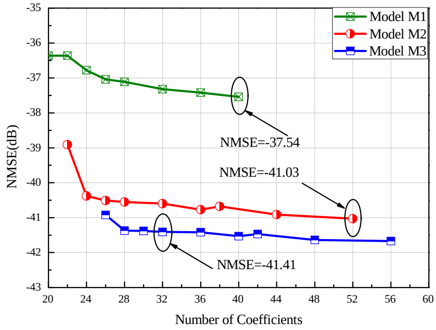

Figure 4. Comparison of the three models in terms of the NMSE as a function of the number of coefficients. Each point is represented by the lower NMSE at each number of coefficients.

Table 1. NMSE comparison of different models.

K_b/K_c	Q_b/Q_c	M1		M2		M3	
		No. coef	NMSE (dB)	No. coef	NMSE (dB)	No. coef	NMSE (dB)
3	0	22	−34.05	22	−34.56	26	−35.38
3	1	24	−34.32	24	−34.96	28	−35.92
3	2	26	−34.64	26	−35.05	30	−36.00
3	3	28	−34.74	28	−35.14	32	−36.07
5	0	23	−34.05	24	−35.25	28	−36.27
5	1	26	−34.72	28	−35.99	**32**	**−37.18**
5	2	29	−35.10	32	−36.14	36	−37.35
5	3	32	−35.25	36	−36.27	40	−37.48
7	0	24	−34.05	26	−35.38	30	−36.42
7	1	28	−34.82	32	−36.31	36	−37.35
7	2	32	35.26	38	−36.53	42	−37.61
7	3	36	−35.43	44	−36.66	48	−37.80
9	0	25	−34.05	28	−35.46	32	−36.50
9	1	30	−34.86	36	−36.38	40	−37.43
9	2	35	−35.36	44	−36.61	48	−37.73
9	3	**40**	**−35.58**	**52**	**−36.74**	56	−37.94

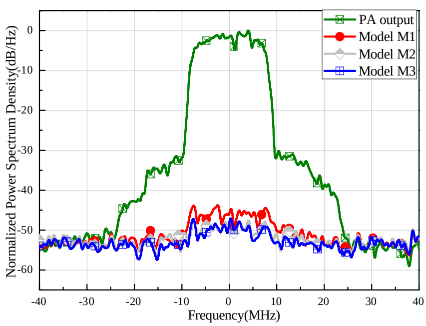

Figure 5. EPSD plots for the single carrier 16QAM signal test.

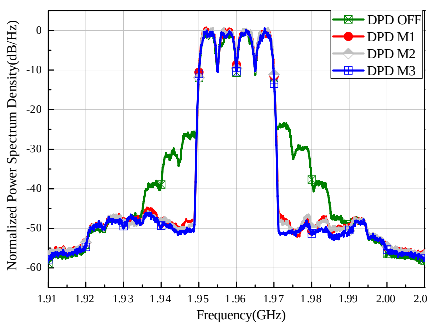

Figure 6. Comparison of the output spectra for the 4-carrier WCDMA signal test.

and number of coefficients, compared with the HME model and the GMP model, the new proposed Volterra-based model uses the least coefficients but achieves the highest accuracy in both time and frequency domains.

4.2. DPD Performance Assessment

The proposed model, as well as the HME and GMP models were applied to DPD. The model dimensions were set to the values highlighted in Table 1 and Fig. 4. ACPR was considered to assess the DPD performance.

The measured ACPRs and number of coefficients for the 4-carrier WCDMA signal and the single carrier 16QAM signal are listed in Table 2 and Table 3 respectively. In comparison with the HME model, the proposed model shows significant ACPR improvements of 2.90/1.34 dB and 2.61/3.54 dB for the two test signals respectively,and a 20% reduction in the number of coefficients. The proposed model also outperforms the GMP model with ACPR improvements of 2.26/0.42 dB and 1.38/0.82 dB for the two test signals respectively, but with approximately 40% decrease in the number of coefficients. The measurement results in terms of ACPR demonstrate the superiority of the proposed model.

Figures 6 and 7 show the comparison of the output spectra for the 4-carrier WCDMA signal and the single band 16QAM signal, respectively. The figures prove that the proposed model achieves the best DPD performance once again.

Table 2. Comparison of ACPRs for 4-carrier WCDMA signal.

DPD approaches	ACPR of upper band (dBc)	ACPR of lower band (dBc)	No. coef
DPD OFF	−22.53	−24.41	
DPD M1	−47.69	−48.68	40
DPD M2	−48.33	−49.60	52
DPD M3	**−50.59**	**−50.02**	**32**

Table 3. Comparison of ACPRs for single carrier 16QAM signal.

DPD approaches	ACPR of upper band (dBc)	ACPR of lower band (dBc)	No. coef
DPD OFF	−34.32	−36.61	
DPD M1	−46.49	−46.55	40
DPD M2	−47.72	−49.27	52
DPD M3	**−49.10**	**−50.09**	**32**

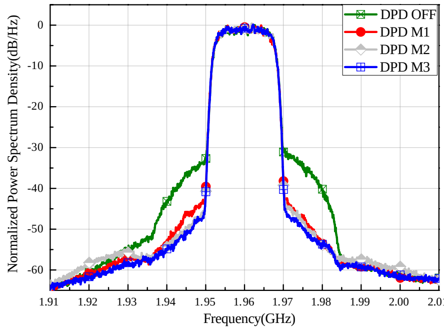

Figure 7. Comparison of the output spectra for the single carrier 16QAM signal test.

5. CONCLUSION

In this paper, a new accurate Volterra-based model is proposed for behavioral modeling and DPD of RF PAs. It extends the GMP model with specific cross terms, and these augmented terms significantly increase the model's performance. The model's performance in the behavioral modeling and DPD of a highly nonlinear Doherty PA driven by two signals (a 4-carrier WCDMA signal and a single carrier 16QAM signal) was assessed and compared to that of the HME and GMP models. In the behavioral modeling application, the calculated results in terms of NMSE, EPSD and number of coefficients indicate that the proposed model achieves the highest accuracy with the lowest computational complexity. In the DPD application, the measurement results also clearly demonstrate the superiority of the proposed model.

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