Worst-Case Models of RF Front-End Nonlinearity for Discrete Nonlinear Analysis of Electromagnetic Compatibility

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Abstract — **A worst-case approach to development of nonlinear models for RF front-ends and components is proposed. This approach makes it possible to avoid the omission of nonlinear interference in process of the computer simulation, which is very important for EMC analysis. Based on the proposed approach, we developed a technique for synthesis of the models intended for the use in framework of the discrete nonlinear analysis technology. For validation of the developed technique, nonlinear behavioral model of a microwave amplifier was synthesized.**

Keywords — receiver, intermodulation, desensitization, behavior simulation, worst-case model

I. Introduction

Co-site operation of radio equipment (radars, communication, navigation, etc.) is characterized by the presence of powerful out-of-band signals at antenna inputs of radio receivers. These signals can cause a nonlinear interference (intermodulation, desensitization, reciprocal mixing, etc.) in the receivers [1, 2, 3, 4]. Therefore, the prediction of the receivers' nonlinear behavior in the expected electromagnetic environment (EME) is a very important part of co-site electromagnetic compatibility (EMC) analysis.

In order to solve the prediction problem, a discrete nonlinear analysis (DNA) technology has been developed and successfully used [5, 6, 7]. This technology has a number of essential features to analyze EMC: 1) simulation in wide frequency and dynamic ranges, 2) account for combined influence of all the fundamental types of nonlinear effects (intermodulation, desensitization, cross-modulation, spurious responses, reciprocal mixing), 3) high computational efficiency (the DNA's computational advantage over traditional techniques [1, 8] grows rapidly with increasing EME complexity and with increasing order of the nonlinear effects).

In order to implement the advantages of the DNA technology in full, high-quality nonlinear models of RF front-ends as well as their components (first of all – amplifiers and frequency mixers) are necessary. At the same time, DNA-compatible nonlinear models synthesized by the known techniques may underestimate the levels of nonlinear interference substantially, which reduces the practical value of such models. *The objective of this paper* is to develop a technique for synthesis of worst-case (i.e., avoiding the underestimation of interference) nonlinear models intended for EMC analysis by the instrumentality of the DNA technology.

The following problems were solved in order to attain the objective. Drawbacks of the known techniques for synthesis of nonlinear DNA-compatible models are characterized (Section II). Taking into account the peculiarities of EMC analysis problem, a worst-case approach to nonlinear model synthesis is proposed (Section III). Based on this approach, a quality criterion of such models is described (Section IV). A technique for synthesis of nonlinear DNA-compatible models satisfying the introduced criterion is developed (Section V) and validated by a microwave amplifier example (Section VI).

II. Drawbacks of Known Techniques for Synthesis of Nonlinear DNA-Compatible Models

A. Peculiarities of Nonlinear DNA-Compatible Models

The efficiency of the DNA technology is mainly caused by simulation of nonlinearities in the time domain, based on transfer characteristics for instantaneous values of signals (not for complex envelopes) [5, 6]. The use of polynomial models for nonlinearities is the second peculiarity of the DNA technology (such models make it possible to achieve a high dynamic range of nonlinear analysis – up to 300 dB) [5, 6]:

$$y(x) = \sum_{k=0}^{M} a_k \cdot x^k \ , \quad (1)$$

where x and y are instantaneous values of voltages at the input and output of the nonlinearity, M is the order of the model, and $\{a_k\}$ are the coefficients of the model.

The interrelationship between the instantaneous transfer characteristic (ITC) (1) and the one-tone amplitude response (AR) of order N (AR-N) is given in [9], the interrelationship between the one-tone and two-tone ARs is considered in [10], and the direct calculation of the two-tone ARs based on the ITC is described in [11, 12]. In particular, the AR for desensitization (DSAR) and the ARs for two-signal intermodulation of order N (IMAR-N) are the special cases of the two-tone ARs.

B. Classical Technique

The classical technique of the model synthesis is based on one-to-one conversion of the small-signal level of a nonlinear product of order N into the absolute value of the coefficient a_N of the ITC (1) [2, 8, 13]. The classical technique is applied to DNA in [14, 15]: the small-signal levels of intermodulation products falling into the first harmonic zone are expressed in terms of the spurious-free dynamic ranges for intermodulation (IDRs). These IDRs are the initial data for the synthesis.

If we refuse the small-signal approach, the coefficients of the model (1) are calculated by the formula

$$a_N = \frac{(2/X_{\min})^{N-1}\cdot\sigma_N\cdot G_0}{C_N^{|n_{2N}|}\cdot IDR_N^N\cdot SIR_{out}} - \sum_s \gamma_{N+2s}(X_{\min}\cdot IDR_N)^{2s},$$
$$N = M, M-1, \ldots 2, \quad n_{2N} = -\mathrm{Trunc}[N/2],$$
$$s = 1, 2, \ldots L_N, \quad L_N = \mathrm{Trunc}[(M-N)/2], \qquad (2)$$
$$\gamma_{N+2s} = \frac{a_{N+2s}\cdot C_k^s}{C_N^{|n_{2N}|}\cdot 2^{2s}}\cdot\sum_{i=0}^{s} C_s^i\cdot C_{N+s}^{|n_{2N}|+i}, \quad C_n^m = \frac{n!}{m!\cdot(n-m)!},$$

where $X_{\min}$ is the sensitivity (i.e., the minimum amplitude of the desired signal at the nonlinearity input); IDR_N is the IDR of order N; SIR_{out} is the required signal-to-interference ratio (SIR) at the output of the nonlinearity (the values $X_{\min}$, IDR_N, and SIR_{out} are defined in (2) by the use of the voltage amplitudes); σ_N is the sign describing the initial phase of the N-th-order intermodulation (IM) product at the output of the nonlinearity if the input signal level is equal to the susceptibility to IM of order N.

The sum in (2) characterizes the influence of the higher-order nonlinearity on IDR_N (and thereby on a_N); if we neglect this influence by taking $\gamma_{N+2s}=0$ then (2) comes to the known small-signal formula [14, 12].

The signs σ_N in (2) could in principle be found by synchronous or vector measurements [16]. But if this is impossible (e.g., if it is necessary to extract the model only from the standardized characteristics given in specification) or unreasonable (e.g., as a result of the high cost of vector measurements) then the signs must be defined in such a way that the necessary shape of AR-1 and IMARs of the synthesized model is provided. First of all, the models having equal signs of the coefficients a_N held by the higher ($N>1$) powers of the same evenness in (1) should be considered: $sign(a_N)=sign(a_{N+2})$, $N=2,3,\ldots$ (if the influence of the higher-order nonlinearity on IDR_N is small then, as it follows from (2), the signs of the coefficients a_N coincide with the signs σ_N: $sign(a_N)=\sigma_N$). Such set of the signs does not guarantee the absence of underestimation of IMARs by the model, but nevertheless it provides (due to cophasal accounting for the influence of different-order nonlinearities) the absence of notches in higher-order IMARs – ref. Fig. 5 in Section VI.B.

On the contrary, the sign interleaving proposed in [14, 15, 12] usually causes the appearance of notches in IMARs. As an example, let us consider the model "C09pnpnp" extracted from the dataset given in Section VI.A with the use of the following signs: $(\sigma_1,\sigma_3,\sigma_5,\sigma_7,\sigma_9)=(1,-1,1,-1,1)$ (Fig. 1). The presence of notches in IMAR-3 and IMAR-7 of this model can cause a severe underestimation and even miss of IM interference of 3-rd and 7-th orders.

Let us consider the drawbacks of the classical technique:

1) Since IDR of order N (IDR-N) characterizes only one point of the corresponding IMAR-N (the coordinates of which are N-th-order intermodulation susceptibility levels with respect to the input and output [2, 13]), the model extracted from IDRs can in the general case exactly predict IMAR-N at that point only. If the point corresponding to IDR-N belongs to the small-signal region of the IMAR-N (in practice, this holds true only for IMARs of low orders, usually, not above the 9th), then the model is able to exactly reproduce the IMAR-N in the whole small-signal region (in which the influence of nonlinearity of orders $N+2, N+4, \ldots$ on IMAR-N can be neglected, so the slope of IMAR-N in dB/dB is constant and equal to its order N [13]). Outside of the small-signal region, no constraints are imposed on IMARs, so the synthesized models may severely underestimate and even miss the IM interference.

2) The technique makes it possible to synthesize a small-signal model only (such model does not describe the AR-1 saturation region which causes the desensitization) even if the IDRs of very high orders are given [15].

The refusal of the small-signal assumption in (2) does not eliminate these drawbacks but only provides the exact passage of IMARs of all orders under analysis through the points defined by the IDRs (ref. the 9-th-order model "C09pnpnpH" in Fig. 1).

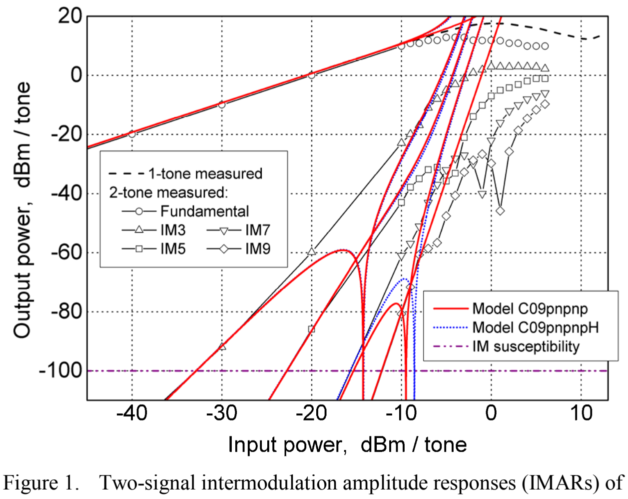

Figure 1. Two-signal intermodulation amplitude responses (IMARs) of the MMIC amplifier: measurements vs. simulation by classical models "C09pnpnp" and "C09pnpnpH"

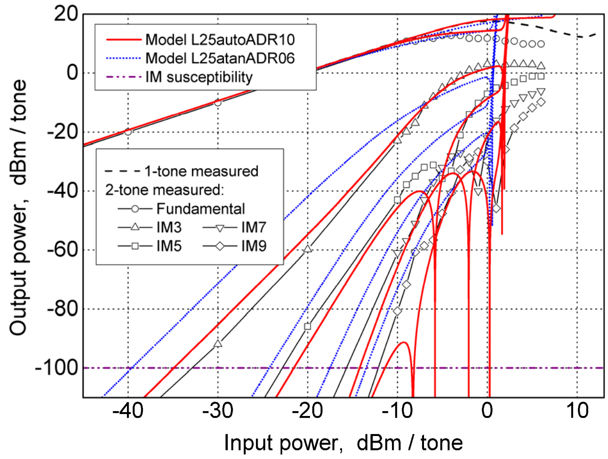

Figure 2. Two-signal intermodulation amplitude responses (IMARs) of the MMIC amplifier: measurements vs. simulation by models "L25autoADR10" and "L25atanADR06"

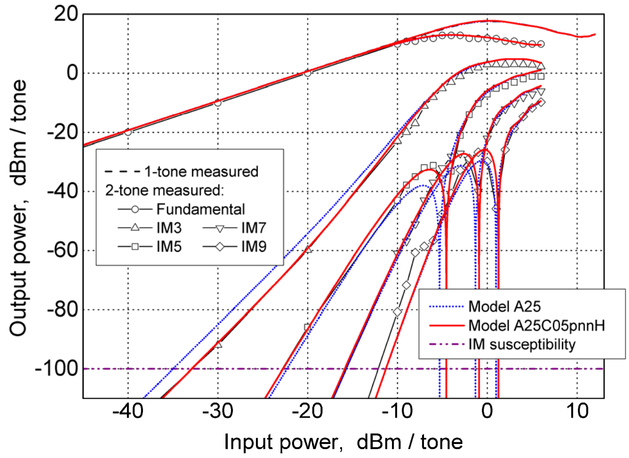

Figure 3. Two-signal intermodulation amplitude responses of the MMIC amplifier: measurements vs. simulation by models "A25" and "A25C05pnnH"

C. Synthesis by Choosing the Best-Fit Theoretical Model from Library

In contrast to the traditional one, this technique makes it possible to obtain a physically-adequate (but, as a rule, quantitatively-inaccurate) description for the saturation region of the nonlinearity, i.e., to correct the drawback 2 from Section II.B. This is achieved by the use of an intermediate theoretical model for ITC – such model must have a small-signal quasi-linear region and a saturation area [15]. The library of intermediate models includes the following kinds of double-sided limiters (formulas are given in [15, 17]): "Hard limiter", "Sine limiter", "Exponential limiter", "Arctangent limiter", "BJT differential amplifier", "FET differential amplifier", "Error-function limiter".

The technique is implemented by the following algorithm [15]. At first, a normalized intermediate model is chosen; this model is then approximated in the interval $|x| < ADR$ by a polynomial of degree M by the specially developed interpolation technique. After that, the desensitization dynamic range and the saturation level are found, and the polynomial model is denormalized. Finally, the IDRs are computed for the denormalized model, and a model quality criterion is estimated as RMS error (or as maximum error) between the computed and given IDRs expressed in dB. These steps are repeated for the other polynomial approximation parameter values and for the other intermediate models, and then the best model (which minimizes the quality criterion) is chosen.

Since the quality criterion requires the approximation of IDRs only, the technique under consideration has drawback 1 from Section II.B. For example, the 25-th-order model "L25autoADR10" extracted from the dataset given in Section VI.A by the automated selection (Fig. 2) underestimates the levels of IMAR-5, -7, and -9 both in the small-signal region (due to IDR approximation errors) and as a result of the notches.

The modeling of intermodulation arising in radio receivers and their components is reasonable if the level of total interference at the input does not exceed the susceptibility to desensitization (this limits the types and orders of intermodulation to be modeled). The susceptibility to 1-dB-desensitization may be roughly estimated (for the exact estimation, it is necessary to analyze the DSAR) as a 1-dB-compression point of the corresponding AR, namely of AR-1 for the continuous-wave (CW) interference [10 – eq.(13)] and of IMAR-1 for the two-tone one. Therefore, the model of nonlinearity must describe the IMARs adequately up to roughly the 1-dB-compression point of IMAR-1, and the notches located in the IMARs of the model above this point (which is equal to -8 dBm for the example given in Fig. 2) may be left out of account.

D. Synthesis by Approximation of One-Tone Amplitude Characteristics

The model is synthesized by the following algorithm: first, the AR-1 is approximated by a polynomial, and then the resulted polynomial model of AR-1 is transformed into the polynomial model of ITC by conversion of its coefficients [18, 6, 19]. If the simulated object exhibits the amplitude-to-phase conversion, the technique makes it possible to extract the instantaneous quadrature models from the complex ARs [6, 19]. The 25-th-order model "A25" (Fig. 3) extracted from the dataset given in Section VI.A by the technique developed in [19] almost coincides with the model in [20, Fig. 15].

The information about the IMARs' behavior in the small-signal region is hidden under the noise caused by the errors in the initial data describing the AR-1 [19, Fig. 4]. This information can not always be recovered by filtering of the noise (i.e., by choosing such order of the model that provides the best approximation of IMARs), as proposed in [20].

Therefore, in this paper, we propose to embed a classical model in the AR-approximation-based model by the following algorithm: 1) to find the absolute values of the coefficients for the M_C-th-order classical model of the ITC (see Section II.B); 2) to take the signs of the coefficients for the classical model identical with the signs of the corresponding coefficients for the M-th-order model ($M > M_C$) synthesized by the technique [19]; 3) to compute the coefficients for the classical model of the AR-1 [9, eq. (T5)], [19, eq. (3)]; 4) to approximate the AR-1 by a polynomial of degree M by the technique [19], but holding the low-order coefficients “frozen” [21, p.674] at the values computed for the classical model of the AR-1; 5) to transform the obtained model of AR-1 into the ITC model by conversion of its coefficients. The proposed algorithm makes it possible to improve the approximation of the IMARs in the small-signal region (in Fig. 3, see the model “A25C05pnnH”, for which $M = 25$, $M_C = 5$), but the increase in order M_C of the embedded classical model causes the need of significant increase in order M of the “full” model (which is a limitation of the algorithm).

The technique provides a practically exact approximation of AR-1, IMAR-1, and DSAR [6 – Fig. 14] in the whole range of input signal levels up to deep saturation, but the synthesized model may underestimate high-order IMARs and/or have notches in the high-order IMARs. For example, both models given in Fig. 3 underestimate IMAR-9 in the small-signal region by 6…10 dB (this is a drawback) and they have notches in IMAR-5, -7, -9 (these notches are not a drawback since they are located in the desensitization region – see Section II.C).

Note that the IMARs of synthesized models are computed in low resolution in the most of previous papers (e.g., in [6], they are computed at the grid of input amplitudes that is used for the measurements), so the notches in the IMARs can not always be clearly recognized in graphs.

III. Worst-Case Approach to Development of Nonlinear Models for EMC Analysis

The traditional approach to modeling problem implies the use of the following quality criterion: the more exact the model describes the given set of object properties, the better the model is. With regard to the initial data given in Section VI.A, this means that the model must reproduce AR-1 and IMAR-1, -3, -5, -7, -9 as exact as possible.

The following peculiarity must be taken into account when developing models for EMC analysis. Characteristics of the device under modeling are subject to variability, which may be caused by the following: change of operating conditions (e.g., of the environment temperature), aging, replacement of a failed device by the other device of the same type. The amount of AR-1 variability can be estimated by a 20 GHz power amplifier example [22]: range (within one standard deviation $\pm\sigma$) of small-signal gain fluctuations in ensemble of single-type devices is $2\sigma = 0.6\,dB$ (if the normal distribution of the fluctuations is assumed then their range will not exceed $6\sigma = 1.8\,dB$ with probability 99.7%); the 1-dB compression point decreases approximately by 1 dB with increasing the temperature from -30 to $70°C$. It can be expected that IMARs exhibit more variability than AR-1, and that the amount of variability increases with increasing the order of IMAR.

The synthesis of a worst-case model is a traditional way to account for the variability in EMC problems. Even in the worst situation, such model guarantees the absence of the interfering signal level underestimation and of the desired signal level overestimation. Then the essence of the worst-case approach to synthesis of nonlinear models can be formulated as follows: the model must eliminate the underestimation of upper envelopes for amplitude responses (ARs) of interfering signals (in this work – for IMAR-3, -5, -7, -9) and the overestimation of lower envelopes for ARs of the desired signal (AR-1 and IMAR-1). Note that the similar approach is used for antennas for a long time [1]: in the unintentional-radiation region, the worst-case model of antenna pattern is defined as an upper envelope of ensemble of the patterns of single-type antennas.

Rigorously, for each given level of input signal, the AR envelope value is defined as a quantile of the probability distribution of the AR values in ensemble of single-type devices, their age, and possible conditions of their operation: the lower envelope value is defined as α -quantile, and the upper envelope value – as $(1-\alpha)$ -quantile, where α is the significance level (by default, one may take $\alpha = 5\%$).

But the ensembles of ARs are rarely known in practice (ARs are usually measured for just one device operating in the worst conditions), therefore we have to estimate the AR envelopes heuristically (i.e., based on just one realization), e.g., in the following way. AR-1 and IMAR-1 themselves can be used as estimation of the lower envelopes of AR-1 and IMAR-1. In order to estimate the upper envelopes of IMARs-3, -5, -7, -9 it is necessary to transform these IMARs in such a manner that they do not have notches (if a notch in IMAR of the device moves or disappears as a result of the variability then the remaining notch in IMAR of the model may cause the miss of interference). The search and elimination of the notches in IMARs may be performed by hands (the envelopes obtained in this way are shown by dotted lines in Figs. 5 and 6) or an automation algorithm may be developed.

IV. Quality Criterion of Nonlinearity Models Intended for EMC Analysis

On the base of the worst-case approach, a quality criterion of nonlinearity models intended for EMC analysis can be developed by taking into account the following.

1) The worst-case model must not show optimism; but it must not be too pessimistic, otherwise the model becomes useless for practice. So, for each AR $Y_i(X)$, the preliminary criterion of the nonlinearity model quality (adequacy) must be formulated as limits $[\Delta Y_{\min}, \Delta Y_{\max}]$ for the envelope approximation error $\Delta Y_i(X) = Y_i^*(X) - E_{Y_i}(X)$, where $Y_i^*(X)$ is the AR of the model, $E_{Y_i}(X)$ is the envelope of the AR $Y_i(X)$, and all quantities in this formula are expressed in dB. Let us define the approximation adequacy range as an input amplitude interval $[X_{A\min}, X_{A\max}]$ in which the error ΔY_i is within the limits $[\Delta Y_{\min}, \Delta Y_{\max}]$.

2) In order to choose the best one from the adequate models (which fit the preliminary criterion), it is reasonable to use the weighted integrated quality criterion (absolute or error-squared) that makes it possible to account not only for the error value ΔY_i but also for the size ΔX of the input amplitude interval in which this error is observed. Note that the use of the integrated error without the preliminary selection of the adequate models may cause the miss of spikes and/or notches in the AR.

TABLE I. SECONDARY PARAMETERS OF INITIAL DATA SET

Parameter	Value
Sensitivity (X_{min}), dBm	-120.7
1-dB compression point (X_{1dB}), dBm	-3.8
Dynamic range for desired signal (SDR), dB	116.9
Small-signal gain (G_0), dB	20.7
SIR at the output (SIR_{out}), dB	0
IM susceptibility referred to the output (Y_0), dBm	-100
IDR-3 (IDR_3), dB	87.8
IDR-5 (IDR_5), dB	97.9
IDR-7 (IDR_7), dB	105.0
IDR-9 (IDR_9), dB	108.5
Max. input signal (X_{max}), dBm	12
Max. dynamic range of approximation (ADR_{max}), dB	15.8
Resistances of source and load[a] (R), Ohm	50

a. Needed to convert the power into the voltage and vice-versa

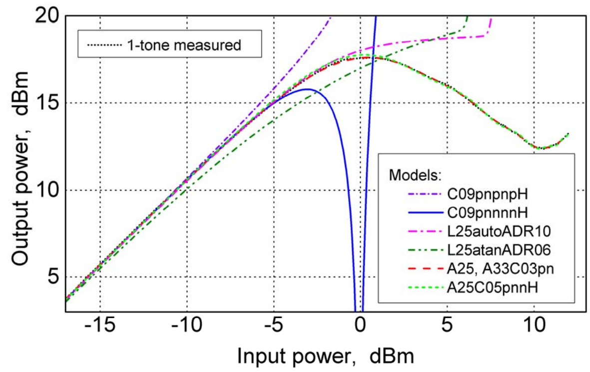

Figure 4. Desired signal amplitude response (AR-1) of the MMIC amplifier: measurements vs. simulation by different models

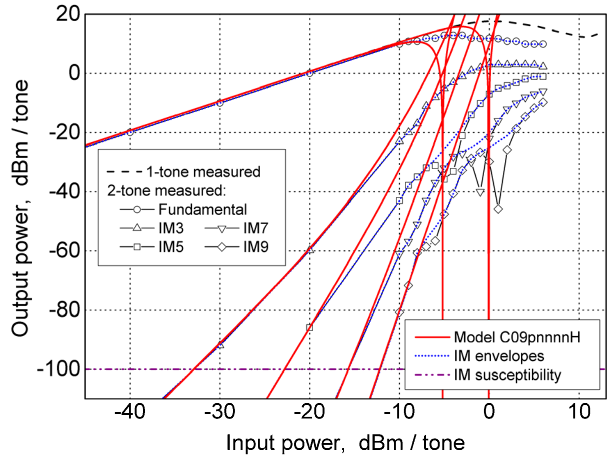

Figure 5. Two-signal intermodulation amplitude responses (IMARs) of the MMIC amplifier: measurements vs. simulation by model "C09pnnnnH"

3) The step of AR argument grid used for computation of the criterion must be small (not more than 0.1 dB); otherwise the notches in IMARs may be missed.

V. TECHNIQUE FOR SYNTHESIS OF WORST-CASE DNA-COMPATIBLE MODELS OF NONLINEARITY

The nonlinear optimization is required in order to synthesize a worst-case model because the criterion (ref. Section IV) involves the maximal and integrated absolute errors. We propose to perform the synthesis by the exhaustive search through the known models having different parameters for the best model in terms of the criterion given in Section IV (this search can be considered as a heuristic optimization):

1) For the classical models (ref. Section II.B), to change the signs σ_N and the presence of account for the influence of the higher-order nonlinearity in (2).

2) For the models described in Section II.C, to change the theoretical model, the approximation dynamic range (ADR), the linearity (i.e., simultaneously the threshold and the level of saturation by equal amounts in dB), and the order M.

3) For models discussed in Section II.D, to change the order M and the order M_C of the embedded classical model.

This technique can easily be automated.

VI. VALIDATION OF WORST-CASE NONLINEAR MODEL SYNTHESIS TECHNIQUE

A. *Initial Data for Synthesis of Models*

As an example for research of performance capabilities and features of nonlinear model synthesis techniques, the experimental results of MMIC amplifier characterization [20 – Figs. 5 and 14] are used. The initial data set contains a table of AR-1 values (Fig. 4) and a table of values of odd-order (1, 3, 5, 7, 9) IMARs measured in the first harmonic zone (Fig. 5). Numerical characteristics of the dataset are given in Table I: the signal-to-interference ratio (SIR) at the output and the sensitivity are defined by the author because these parameters depend on the system in which the simulated amplifier is used; the rest of characteristics are computed on the base of AR-1 and IMARs. For each of the high-order (3, 5, 7, 9) IMARs, the point corresponding to the intermodulation susceptibility level Y_0 referred to the output is located in the small-signal region, because the slope (dB/dB) of IMAR-N in this point is equal to its order N (ref. Fig. 5).

B. *Results of Model Synthesis*

The worst-case models are synthesized by the technique given in Section V. The following parameters of the criterion (ref. Section IV) are used for the synthesis: the model must reproduce AR-1 and IMAR-1 (the permissible error limits are [-1, 1] dB in the linear region and [-3, 1] dB in the regions of "knee" and saturation; the 1-dB-compression point X_{1dB} of the initial data is considered as the upper bound of the linear region – ref. Table I) and the upper envelops of IMAR-3, -5, -7, -9 (the error limits are [-1, 10] dB).

Among the classical models, the 9-th-order model (Fig. 5) synthesized with the use of the signs $(\sigma_1, \sigma_3, \sigma_5, \sigma_7, \sigma_9) = (1, -1, -1, -1, -1)$ and with consideration for the influence of the higher-order nonlinearity (ref. Section II.B) is proven to be the best. The upper bound of the model adequacy range is caused by going of IMAR-5 approximation error out of the permissible limits. This bound is of -3.8 dBm referred to AR-1 (it is 6 dB less if refer to IMARs), and it is equal to 1-dB compression point of AR-1. So, the maximal desensitization (the decrease in level of a weak desired signal) reproduced by the model is about 1 dB for CW interference (ref. Section II.C).

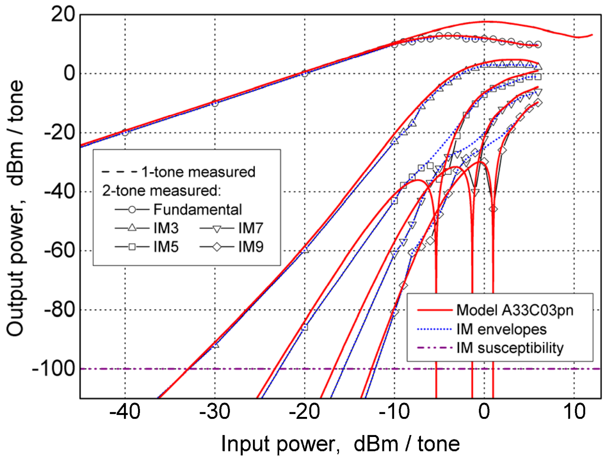

Figure 6. Two-signal intermodulation amplitude responses (IMARs) of the MMIC amplifier: measurements vs. simulation by model “A33C03pn”

Based on the technique given in Section II.C, we failed to synthesize a model which is able to reproduce all above-stated characteristics adequately: the best model (“L25atanADR06”) providing the worst-case approximation of IMAR-3, -5, -7, -9 shows intolerable (about 20 dB) pessimism for IMAR-3 in the small-signal region (ref. Fig. 2). This result is caused by the following: in the library, we have no theoretical models which are close to the measured nonlinearity.

The worst-case model “A33C03pn” synthesized by the algorithm proposed in Section II.D with $M = 33$ and $M_C = 3$ (Fig. 6) is proven to be the best. The upper bound of the model adequacy range wrt. intermodulation of the higher orders (5, 7, 9) is caused by going of IMAR-5 approximation error out of the permissible limits. This bound is of -3.1 dBm referred to AR-1 (-9.1 dBm if refer to IMARs, i.e., it approaches the rough boundary of the desensitization region – ref. Section II.C). The excellent approximation of AR-1, IMAR-1, -3 in the whole range of the initial data makes it possible to analyze the desensitization and IM-3 for input signals which have the maximal instantaneous power up to +15 dBm.

VII. Conclusion

The worst-case approach and nonlinear model quality criterion proposed in this work are correct for performing the nonlinear analysis of EMC not only by the DNA method but also by the other (e.g., traditional) methods.

Monte Carlo modeling of the variability (i.e., the repeated analysis of interference for a random sample of nonlinearity realizations) is an alternative to the worst-case approach. For Monte Carlo modeling, it is convenient to use the nonlinear model synthesis technique described in Section II.D because that technique provides more accurate approximation of the characteristics for each realization of the nonlinearity. Note that Monte Carlo method is popular for modeling of interference in bundles of cables [23].

References

[1] A handbook series on electromagnetic interference and compatibility, Vol.7: Duff W.G. Electromagnetic compatibility in telecommunications. Interference Control Technologies, Inc., Gainesville, VA, 1988.

[2] Rohde U.L., Whitaker J. Communications Receivers: DSP, Software Radios, and Design, 3rd Edition, McGraw-Hill, New York, 2000.

[3] Lustgarten M.N. Significant receiver intermodulation (RIM) products // IEEE Symp. on EMC, 1979, pp. 314–318.

[4] Mordachev V.I., Sinkevich E.V. Experimental Analysis of Radio Receiver Susceptibility to Out-of-Band Interference by Means of Double-Frequency Test System // Proc. of 10-th Int. Symp. on EMC “EMC Europe 2011”, UK, York, Sept. 26-30, 2011, pp. 405–411.

[5] Mordachev V.I., Sinkevich E.V. “EMC-Analyzer” expert system: improvement of IEMCAP models // XIX Int. Wroclaw Symp. on EMC. 2008, pp. 423–428.

[6] Loyka S.L., Mosig J.R. New behavioral-level simulation technique for RF / Microwave applications. Part I: Basic concepts // Intern. J. RF and Microwave CAE. 2000. Vol. 10, No. 4, pp. 221–237.

[7] EMC-Analyzer. Mathematical models and algorithms of electromagnetic compatibility analysis and prediction software complex. Minsk, 2013.

[8] Smith J.L. Intermodulation prediction and control. Gainesville, VA, 1993.

[9] Blachman N.M. Detectors, bandpass nonlinearities, and their optimization: inversion of the Chebyshev transform // IEEE Trans. on Information Theory. 1971. Vol. 17, No. 4. P. 398–404.

[10] Blachman N.M. Intermodulation in terms of the harmonic output of a nonlinearity // IEEE Trans. on Acoustics, Speech, and Signal Proc. 1981. Vol. 29, No. 6. P. 1202–1205.

[11] Sea R.G., Vacroux A.G. On the computation of intermodulation products for a power series nonlinearity // Proc. IEEE. 1969. Vol. 57, No. 3, P 337–338.

[12] Cheremisinov D.I. Selection of polynomial model based on intermodulation dynamic ranges // 4th Int. Conf. on New Information Technologies (NITe’2000), Dec. 5-7, 2000, Minsk, Belarus, pp. 133–140 (in Russian).

[13] Pedro J.C., Carvalho N.B. Intermodulation Distortion in Microwave and Wireless Circuits, Artech House, Boston, 2003.

[14] A.F. Aporovich and V.I. Mordachev, “Functional possibilities of the EMC characteristics monitoring of electronic apparatus by the two-frequency probing method” // Proc. 9-th Int. Wroclaw Symp.on EMC, Wroclaw, Poland, 1988, pp. 867–872 (in Russian).

[15] Cheremisinov I.D., Loyka S.L., Mordachev V.I. Synthesis of the polynomial model of nonlinear elements based on intermodulation dynamic ranges // 3rd Int. Conf. on Telecomm. in Modern Satellite, Cable, and Broadcasting Services, Oct. 8-10, 1997, Nis, Yugoslavia, pp. 519–522.

[16] Walker A., Steer M., Gard K.G. A vector intermodulation analyzer applied to behavioral modeling of nonlinear amplifiers with memory // IEEE Trans. on Microwave Theory and Tech. 2006. Vol. 54, No. 5. P. 1991–1999.

[17] Sinkevich E., Mordachev V. Characterization of radio receiver’s front-end nonlinearity by measurement of spurious-free dynamic ranges // 11th Int. Symp.“EMC Europe 2012”, Rome, Sept. 17-21, 2012, 6 p.

[18] Loyka S.L., Cheremisinov I.D. Validation of the high-order polynomial models used in behavioral-level simulation // 4th Int. Conf. on Telecomm. in modern satellite, cable, and broadcasting services. Nis, Yugoslavia, 13–15 Oct. 1999. P. 592–595.

[19] Sinkevich E.V. “AM-PM Conversion Simulation Technique for Discrete Nonlinear Analysis of Electromagnetic Compatibility” // Proc. of VIII-th Int. Symp. on EMC and Electromagnetic Ecology, Saint-Petersburg, Russia, June 16-19, 2009, pp.127-130.

[20] Loyka S.L., Mosig J.R. New behavioral-level simulation technique for RF / Microwave applications. Part II: Approximation of nonlinear transfer functions // Int. J. RF and Microwave CAE. 2000. Vol. 10, No. 4. P. 238–252.

[21] Press W.H. et al. Numerical recipes in C. 2nd ed. Cambridge University Press, 1997.

[22] Bignamini M. et al. Efficient development of highly linear MMIC power amplifiers // 31st European Microwave Conf. GAAS 2001, 24–28 Sep. 2001, London. P. 693–696.

[23] Gonser M. et al. “Simulation of automotive EMC emission test procedures based on cable bundle measurements”, 2012 IEEE MTT-S Intern. Symp. Digest, p.1-3.