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Double-Frequency-Testing-Based Models of 5G FR1 Amplifier Nonlinearity for Rapid Simulation of EMI

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Abstract — **Nonlinear properties of low-power radio-frequency amplifiers similar to those used in 4G/5G mobile-communication equipment of the FR1 frequency range are studied experimentally at frequencies of the n7 band (2500–2570 / 2620–2690 MHz) and the n78 band (3300–3800 MHz) by using the double-frequency test system. High-order polynomial models of transfer characteristics of investigated amplifiers are extracted from the following measured data: double-frequency characteristics of the amplifiers, their single-tone amplitude characteristics, as well as two-tone amplitude characteristics and the interference-free dynamic ranges for 3rd-, 5th-, 7th-, and 9th-order intermodulation in the first harmonic zone. These models are suitable for use in a wide dynamic range of input signals in case of simultaneous modeling of nonlinear effects of all kinds posing a danger to radio reception in a complex electromagnetic environment (EME) created in the mobile-communication frequency bands: both "subtle" effects (intermodulation) and "rough" effects (desensitization, cross-modulation). When using the technology of discrete nonlinear analysis, the obtained models provide high efficiency of computer simulation of nonlinear processes and radio interference occurring in 4G/5G radio equipment and networks in a complex EME.**

Keywords — **mobile communications, 4G, 5G, electromagnetic environment, radio-frequency amplifier, nonlinearity, polynomial model.**

I. Introduction

The extremely intensive development and penetration of wireless technologies and services into all spheres of human activity within the framework of the evolution of mobile communications (MC) 4G→5G→6G is associated with an expected increase by several orders of magnitude in the spatial density of sources of radio-frequency (RF) electromagnetic fields (EMF) – up to 10^6 units/km^2 within the fifth generation (5G) and up to 10^7 units/km^2 within the sixth generation (6G) – with a simultaneous declared increase in the mobile area traffic capacity by many orders of magnitude – up to 10 Mbit/s/m^2 for 5G and up to 1 Gbit/s/m^2 for 6G [1]. This will inevitably lead to a significant complication of the electromagnetic environment (EME) and radio reception conditions in places where 4G/5G/6G equipment is intensively used for industrial and domestic purposes, including an increase in the dynamic range of RF EMF levels by an average of at least 10–20 dB with full scale implementation of systems and 5G and 6G services (taking into account the quantitative relationship established in [2] between the number of RF EMFs present at the input of a radio receiver and their dynamic range). With the existing values of the dynamic range of RF input linearity of modern receivers of base stations and peripheral stations of 4G/5G/6G systems at the level of 60–75 dB, this will inevitably cause a very significant increase in the danger of nonlinear interference to radio reception, primarily intermodulation. Without increasing the linearity of the radio paths of the receivers of base and peripheral stations and developing adequate models of the nonlinearity characteristics of their input elements (describing the behavior of the receiver when powerful signals of the input EME significantly exceed the upper limit of the linear mode of operation of these elements), as well as without effectively managing the complexity of the EME created by 4G/5G/6G MC systems, it will be almost impossible to ensure the efficient operation of these radio paths in case of full implementation of these systems and services. In this regard, it is relevant to study the characteristics of nonlinearity and develop adequate models of the transfer characteristics of RF amplifiers in MC frequency bands of the UHF, SHF, and EHF ranges.

The objective of this work is to measure the nonlinearity characteristics of 5G FR1 (410–7125 MHz) RF amplifiers by using the double-frequency testing technique [3, 4] and to extract adequate models of the transfer characteristics of these amplifiers from the measured data; the extracted models must provide the ability of behavioral simulation of the amplifier operation in a complicated EME containing a lot of signals distributed in a wide dynamic range.

II. Experimental Investigation of Nonlinearity Characteristics of RF Amplifiers

Experimental studies on the nonlinear properties of RF amplifiers (Mini-Circuits ZJL-6G+ and ZX60-6013E-S+) similar to those used in 4G/5G MC equipment of the FR1 range are performed. Measurements of the nonlinearity characteristics of these amplifiers are carried out at frequencies of the n7 band (2500–2570 / 2620–2690 MHz) allocated for 4G MC systems and the n78 band (3300–3800 MHz) proposed for 5G MC. The block diagram of the automated double-frequency test system used in the measurements is shown in Fig. 1.

When carrying out the studies in the vicinity of frequencies 2551 MHz and 3501 MHz, the following characteristics reflecting the nonlinear properties of the analyzed amplifiers are measured: 3D double-frequency characteristics (an example is shown in Fig. 2), 2D double-frequency diagrams (an example is shown in Fig. 3), single-tone amplitude characteristics of the 1st order (AC-1), as well as amplitude characteristics (ACIM) and interference-free dynamic ranges (IDR) for two-signal intermodulation of the 3rd, 5th, 7th, and 9th orders in the first harmonic zone (Table 1).

Figures 4–8 show the measured characteristics of the ZX60-6013E-S+ amplifier nonlinearity in the vicinity of 3501 MHz.

The correctness of the performed measurements is confirmed by the correspondence between the measured values of the main parameters of the amplifiers (gain and 1-dB compression point) and their nominal values given in the manufacturer's specifications.

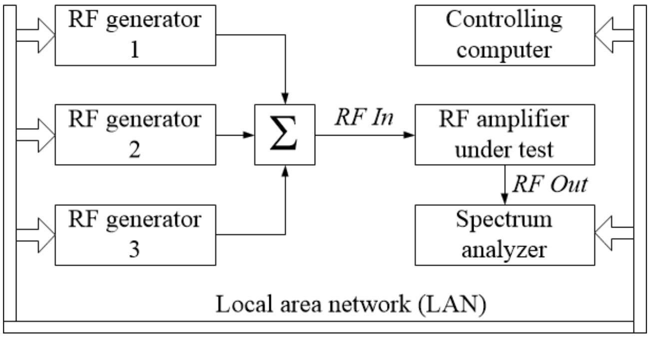

Fig. 1. Block diagram of automated double-frequency test system used for testing the radio frequency amplifiers: RF generators 1, 2, and 3 are Agilent N5181A, E8257D, and E4438C, correspondingly; spectrum analyzer is Agilent N9020A; power combiner is Mini-Circuits ZB3PD-63+

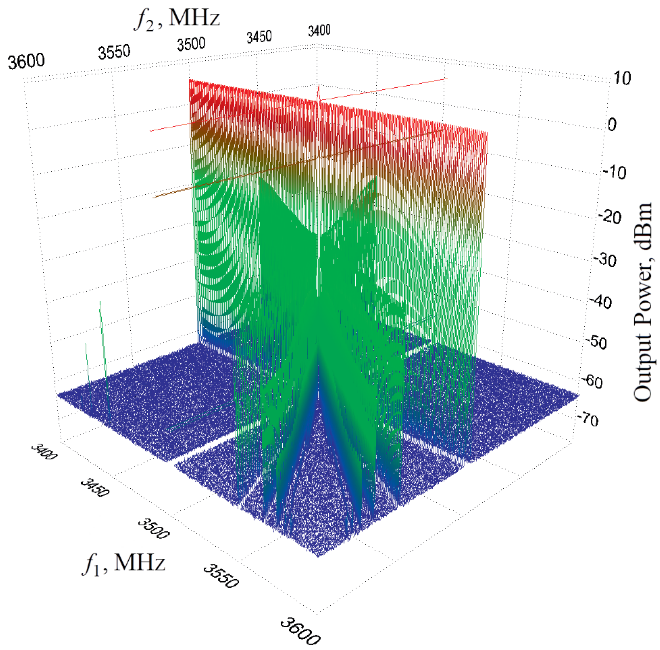

Fig. 2. Double-frequency characteristic of ZX60-6013E-S+ amplifier: power of each input signal is -6 dBm

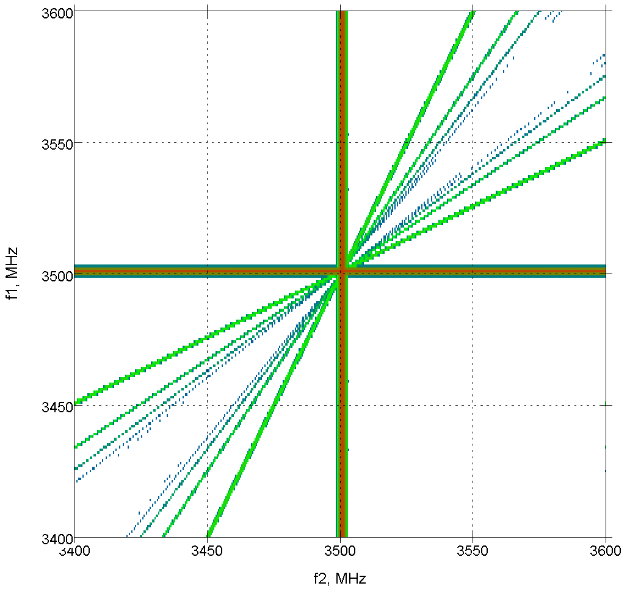

Fig. 3. Double-frequency characteristic of ZX60-6013E-S+ (see Fig. 2) in form of double-frequency diagram: minimum displayed level is -61.5 dBm

Table 1. Values of dynamic range for intermodulation of odd orders for investigated RF amplifiers at different frequencies

Order of IM	Dynamic range, dB			
	ZX60-6013E-S+		ZJL-6G+	
	2551 MHz	3501 MHz	2551 MHz	3501 MHz
3	71,6	70,9	71,2	71,8
5	82,3	81,5	81,4	82
7	85,9	84,8	84,7	85,1
9	87,1	86,2	86,5	86,5

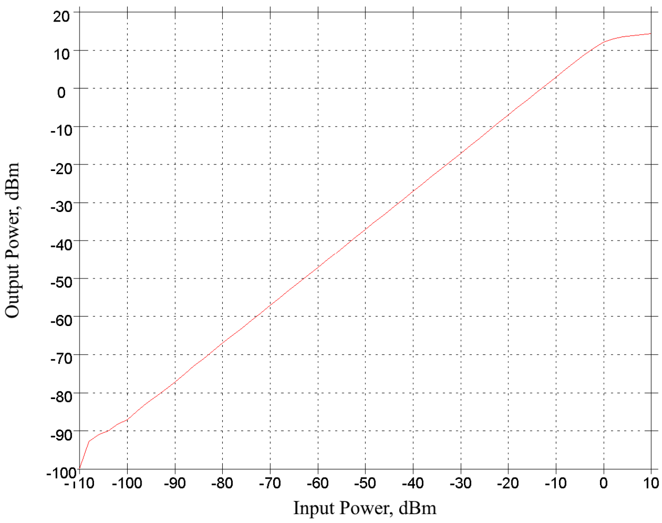

Fig. 4. Single-tone amplitude characteristic of 1st order for ZX60-6013E-S+ amplifier at 3501 MHz

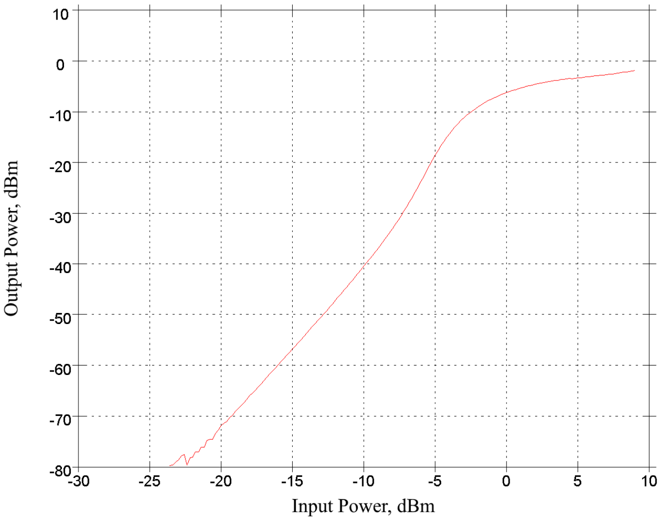

Fig. 5. Equal-signal amplitude characteristic of ZX60-6013E-S+ amplifier for 3rd-order intermodulation: frequencies of input signals are 3321 MHz and 3411 MHz, frequency of intermodulation at the output is 3501 MHz

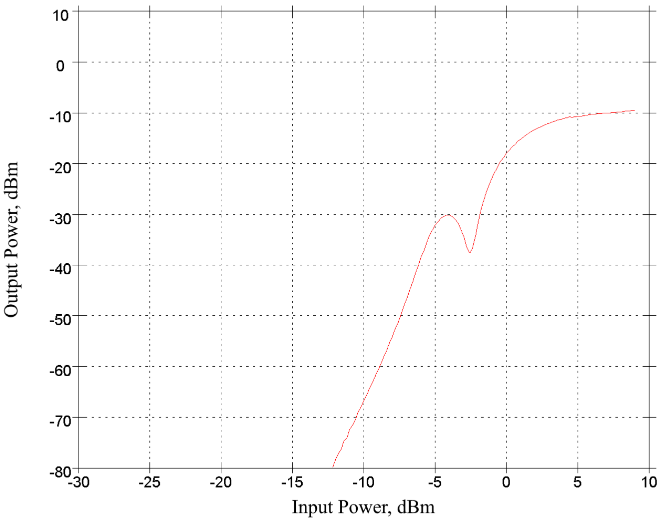

Fig. 6. Equal-signal amplitude characteristic of ZX60-6013E-S+ amplifier for 5th-order intermodulation: frequencies of input signals are 3321 MHz and 3381 MHz, frequency of intermodulation at the output is 3501 MHz

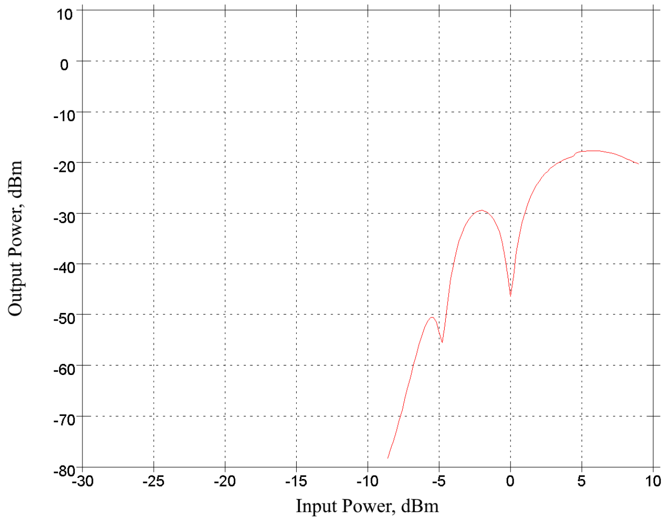

Fig. 7. Equal-signal amplitude characteristic of ZX60-6013E-S+ amplifier for 7th-order intermodulation: frequencies of input signals are 3341 MHz and 3381 MHz, frequency of intermodulation at the output is 3501 MHz

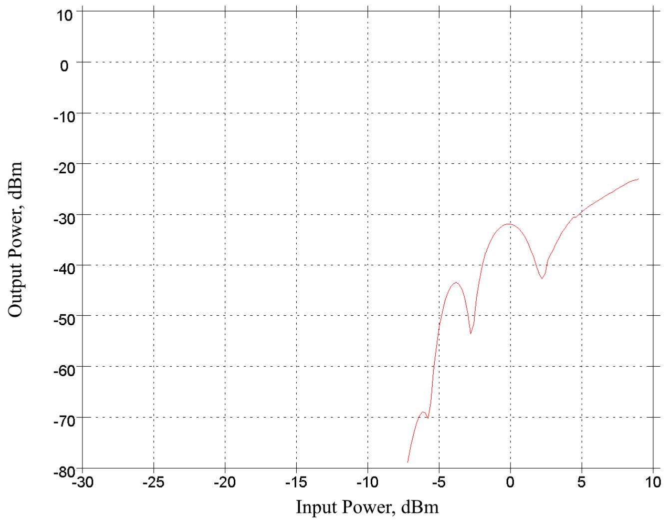

Fig. 8. Equal-signal amplitude characteristic of ZX60-6013E-S+ amplifier for 9th-order intermodulation: frequencies of input signals are 3351 MHz and 3381 MHz, frequency of intermodulation at the output is 3501 MHz

III. Extraction of RF Amplifier Nonlinearity Models From Measured Data

Based on the measured AC-1 and odd-order IDRs (see Table 1), two types of polynomial models are synthesized for the nonlinear transfer characteristics of the ZX60-6013E-S+ and ZJL-6G+ amplifiers at 4G and 5G frequencies by using the techniques given in [5, 6]. 1) Classical 9th-order polynomial models "C09pnnnnH" of the transfer characteristics for the instantaneous signal values are obtained on the basis of the small-signal gain and the IDRs of the 3rd, 5th, 7th, and 9th orders. 2) Combined polynomial models "A37C09pnnnnH", "A27C07pnnnH", "A27C05pnnH", and "A27C09pnnnnH" of 27-37 orders for these transfer characteristics are extracted from useful-signal AC-1 and IDRs of the 3rd, 5th, 7th, and 9th orders. The model synthesis results are given in Tables 2 and 3.

Checking the correctness and analyzing the quality of the synthesized models of amplifier nonlinearity are carried out by comparing the characteristics (AC-1 and ACIM-3, -5, -7, -9) of the models with the measured amplifier characteristics.

As examples, the amplitude characteristics of the ZX60-6013E-S+ models described above and the measurement results in the vicinity of 3501 MHz are plotted in Figs. 9 and 10. As follows from the comparison results shown in Figs. 9

and 10, in this situation, the 9th-order classical model "C09pnnnnH" satisfactorily approximates AC-1 and ACIM of the 3rd, 5th, 7th, and 9th orders in the small-nonlinearity mode (in which the input signal level does not exceed the lower boundary of the desensitization region), and the 27th-order combined model "A27C07pnnnH" adequately reproduces the levels of AC-1 and ACIM of the 3rd and 5th orders in both small- and significant-nonlinearity regions.

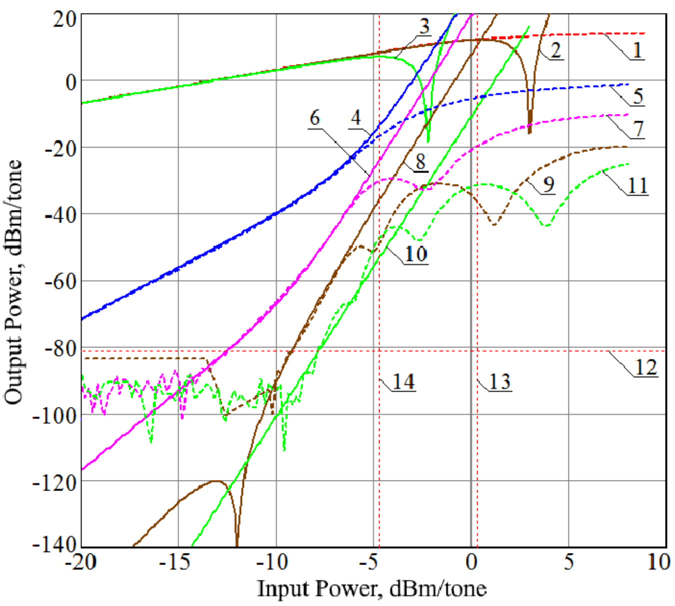

Fig. 9. Measured amplitude characteristics of ZX60-6013E-S+ amplifier and corresponding characteristics of classical model "C09pnnnnH" of its nonlinearity in the vicinity of 3501 MHz

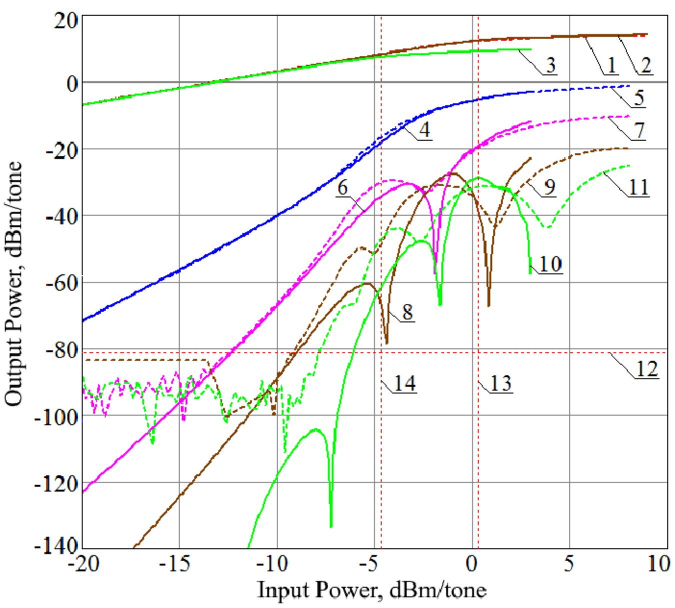

Fig. 10. Measured amplitude characteristics of ZX60-6013E-S+ amplifier and corresponding characteristics of combined model "A27C07pnnnH" of its nonlinearity in the vicinity of 3501 MHz

Table 2. Coefficients of k-th-degree term of 9th-order classical polynomial models "C09pnnnnH" for amplifier transfer characteristics with respect to instantaneous signal values

k	2551 MHz	3501 MHz
	ZX60-6013E-S+	
1	5,01187233627272E+00	4,46683592150963E+00
3	–3,79115739525804E+00	–3,41875895026638E+00
5	–2,91186662445994E+01	–2,41015325335133E+01
7	3,98147207773823E+02	3,00164254336830E+02
9	–6,49934244508732E+03	–5,85961956190790E+03
	ZJL-6G+	
1	4,67735141287198E+00	4,41570447353312E+00
3	–3,53813178804219E+00	–2,41065362321554E+00
5	–2,56237392271981E+01	–1,74863305413972E+01
7	1,59417667531407E+02	2,17449779770705E+02
9	–6,49934244508734E+03	–3,87141225236983E+03

Table 3. Coefficients of k-th-degree term of combined polynomial models for amplifier transfer characteristics with respect to instantaneous signal values

k	ZX60-6013E-S+	
	2551 MHz "A37C09pnnnnH"	**3501 MHz "A27C07pnnnH"**
1	5,01187233627272E+00	4,46683592150963E+00
3	–3,79115739525804E+00	–3,44609013850997E+00
5	–2,91186662445994E+01	–9,70028140264253E+00
7	3,98147207773823E+02	–2,70465533836469E+02
9	–6,49934244508732E+03	4,58787524879355E+03
11	1,01480030648706E+05	–1,21172658596110E+05
13	–7,75265511468785E+06	1,42210112573335E+06
15	1,71406007469750E+08	–8,52923908140936E+06
17	–1,87031429832840E+09	3,00968498916697E+07
19	1,24549865886867E+10	–6,65953658263093E+07
21	–5,56627201956479E+10	9,38547224449889E+07
23	1,75172335386893E+11	–8,20192144456022E+07
25	–3,97447720477309E+11	4,05857091359126E+07
27	6,54730911301783E+11	–8,70302968072780E+06
29	–7,77165806704896E+11	---
31	6,48378065905609E+11	---
33	–3,61006508824642E+11	---
35	1,20491966249457E+11	---
37	–1,82393438286767E+10	---
k	ZJL-6G+	
	2551 MHz "A27C05pnnH"	**3501 MHz "A27C09pnnnnH"**
1	4,67735141287198E+00	4,41570447353312E+00
3	–3,53814123356727E+00	–2,41065362321554E+00
5	–2,53582910793778E+01	–1,74863305413972E+01
7	7,05992100234347E+02	2,17449779770705E+02
9	–5,48724517538845E+04	–3,87141225236983E+03
11	8,84405634294431E+05	–5,61302923440314E+04
13	–6,84016625357666E+06	1,18032587231114E+06
15	3,12212580730648E+07	–8,24969126534329E+06
17	–9,11981992595364E+07	3,12228105659215E+07
19	1,75737016912818E+08	–7,19951931445232E+07
21	–2,22855400361206E+08	1,04348024983096E+08
23	1,79182893656428E+08	–9,31063883242535E+07
25	–8,28792772064902E+07	4,68323085663531E+07
27	1,68075326139024E+07	–1,01779297720287E+07

Line designations in Figs. 9–14 are as follows:

- No. 1 (red dotted) – measured single-tone amplitude characteristic (AC-1) of the amplifier;
- No. 2 (brown solid on top) – single-tone AC-1 for the amplifier model;
- No. 3 (green solid on top) – two-tone AC-1 for the amplifier model;
- blue – equal-signal amplitude characteristic for the 3rd-order intermodulation (ACIM-3): solid No. 4 – model, dotted No. 5 – measurements;
- pink – equal-signal ACIM-5 (solid No. 6 – model, dotted No. 7 – measurements);
- brown – equal-signal ACIM-7 (lower solid No. 8 – model, dotted No. 9 – measurements);
- green at the bottom – equal-signal ACIM-9 (lower solid No. 10 – model, dotted No. 11 – measurements);
- No. 12 – the level of susceptibility to intermodulation at the amplifier output;
- No. 13 – the lower boundary of the desensitization region for single-tone amplitude characteristics (1-dB compression point of single-tone AC-1);
- No. 14 – the lower boundary of the desensitization region for two-tone amplitude characteristics (1-dB compression point of two-tone AC-1).

It has been established that there is an optimal order for the combined polynomial model. For example, the combined model "A27C07pnnnH" (Fig. 10) is obtained by optimizing the total order of the model and the order of the built-in classical model. If, with a fixed order of the built-in classical model (in this case, the 7th order), the total order of the model is reduced below the optimal one (in this case, the 27th), then the approximation of the amplitude characteristics of the amplifier by the model worsens, especially in the regions of knee (transition from the small-nonlinearity region to the limiting region) and limiting, due to the lack of the polynomial degrees of freedom (the 13th-order model "A13C07pnnnH" is shown as an example in Fig. 11). If the total order of the model is increased above the optimal one, then the approximation of the amplifier ACIMs in the small-nonlinearity region deteriorates, since the polynomial model begins to reproduce the measurement errors of AC-1 (Fig. 12 shows the 39th-order model as an example).

To assess the frequency dependence of the nonlinear properties of the investigated RF amplifiers and the models of their nonlinearity, the results of measurements and modeling of the characteristics of the ZX60-6013E-S+ amplifier (similar to those shown in Figs. 9 and 10, but for a central frequency of 2551 MHz) are presented in Figs. 13 and 14. Their analysis indicates a relatively small frequency dependence of the dimensions of the linear region for the single- and two-signal AC-1, and a more significant (and increasing with increasing of intermodulation order) dependence of the shape of the ACIM on frequency.

From a practical point of view, it is very important that the synthesized combined polynomial models (describing both the region of small nonlinearity and the saturation region) are suitable for the simultaneous analysis of nonlinear phenomena of all main types that arise in the RF amplifiers: intermodulation, desensitization, cross-modulation, etc. This property ensures the possibility of adequate behavior simulation of the RF amplifier operation in various EMEs created by 4G/5G/6G MC systems with different spatial densities and radiated powers of RF EMF sources.

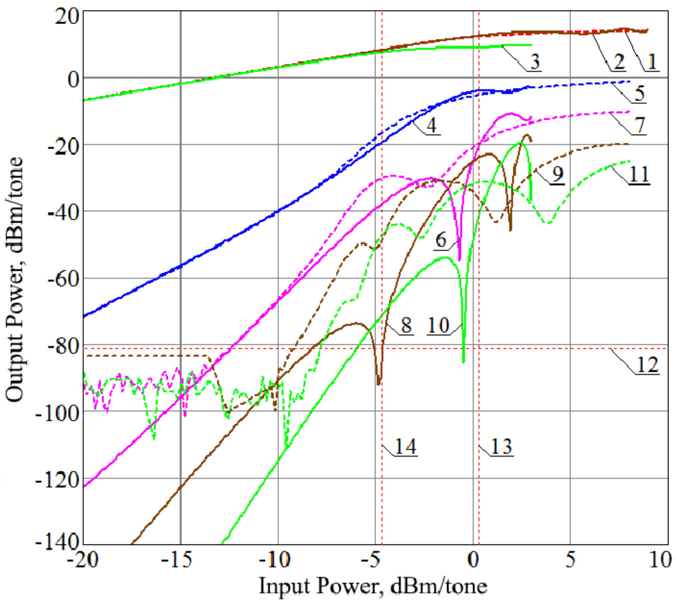

Fig. 11. Measured amplitude characteristics of ZX60-6013E-S+ amplifier and corresponding characteristics of combined model "A13C07pnnnH" of its nonlinearity in the vicinity of 3501 MHz

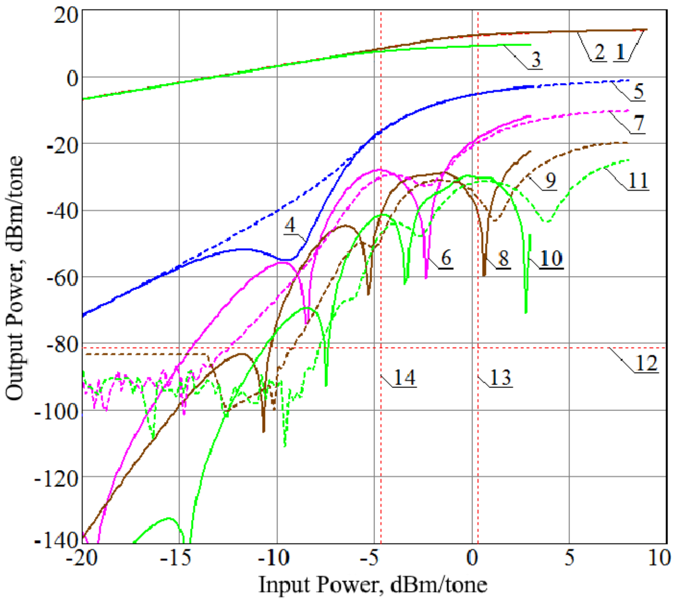

Fig. 12. Measured amplitude characteristics of ZX60-6013E-S+ amplifier and corresponding characteristics of combined model "A39C07pnnnH" of its nonlinearity in the vicinity of 3501 MHz

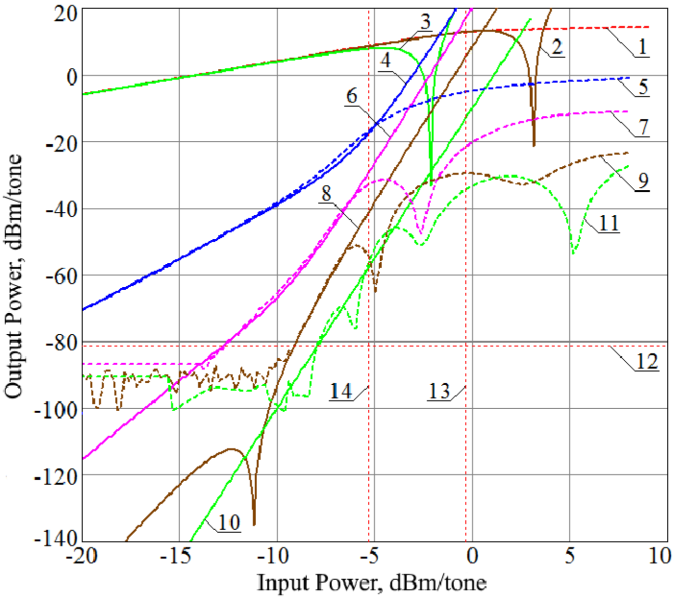

Fig. 13. Measured amplitude characteristics of ZX60-6013E-S+ amplifier and corresponding characteristics of classical model "C09pnnnnH" of its nonlinearity in the vicinity of 2551 MHz

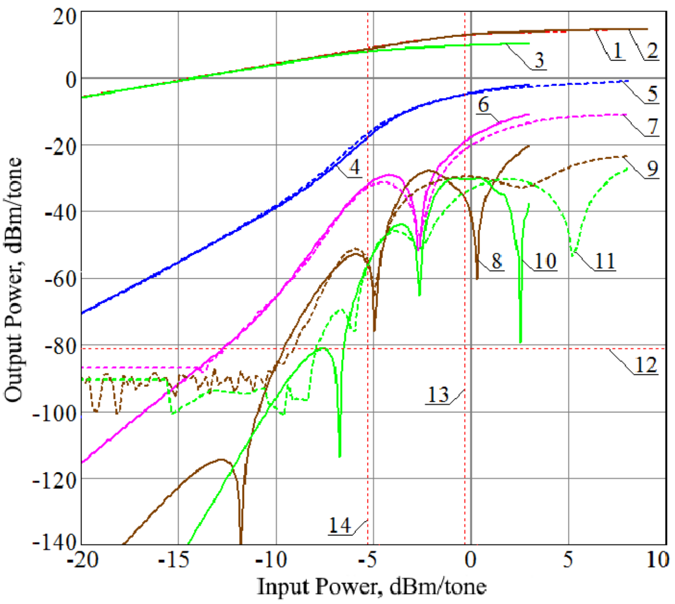

Fig. 14. Measured amplitude characteristics of ZX60-6013E-S+ amplifier and corresponding characteristics of combined model "A37C09pnnnnH" of its nonlinearity in the vicinity of 2551 MHz

IV. Conclusion

The synthesized polynomial models for the transfer characteristics of the RF amplifiers are suitable for use in case of a wide dynamic range of input signals while simultaneously modeling of nonlinear effects of all types that pose a danger to radio reception in complex EME in the MC frequency bands: both "subtle" effects (intermodulation) and "rough" effects (desensitization, cross-modulation).

Since the parameters of high-order polynomial models suitable for describing the nonlinearity of modern low-power RF amplifiers of 5G FR1 frequency range in a wide dynamic range of input signals are absent in the scientific literature, the data given in Tables 2 and 3 can be used as reference. This provides the opportunity for research, efficient modeling, and quantitative analysis of nonlinear processes and radio interference (that arise in equipment and radio networks of 4G/5G/6G MC when operating in a complex EME) by using the technology of discrete nonlinear analysis of the behavior of radio equipment [7]. If the order of polynomial models of nonlinear transfer characteristics is fixed, this technology is invariant to the complexity of EME.

A possible direction for further research is to analyze the variability of nonlinearity characteristics by processing measurement results for several instances of each amplifier.

Acknowledgment

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