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SIGNAL DISTORTION IN POLAR ARCHITECTURE TRANSMITTERS USING CLASS E RF POWER AMPLIFIERS

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Abstract. The trend towards increasing the energy efficiency of transmitters used in radio and telecommunications systems focuses the attention of equipment developers on finding optimal solutions when transitioning from linear power amplifiers (PAs) to amplifiers operating in switching mode. It is shown in the paper that signal distortion level along with high energy efficiency must be considered as an important parameter of PA. Reasons of signal distortions in class E switched-mode PA used in polar architecture transmitters are given. It is shown that most sufficient distortion is caused by phase shift of the load current, which results from the nonlinear change of transistors' output capacitance when amplifying signals with a non-constant envelope. The results of calculations of the error vector magnitude when using multilevel spectrally efficient modulation types, in particular quadrature amplitude modulation (QAM) and amplitude-phase shift keying (APSK), are presented. The results confirmed that for class E PA the most sufficient type of distortion is phase distortion. The results of analytical model are confirmed by simulation. It is shown that for 16-QAM at bit error rate = 10^{-4}, the energy loss is 0.5 dB, while for 16-APSK its value increases to 2.2 dB. The results presented in the paper can be used in the development of signal predistortion methods for switching class E PAs, ensuring a reduction in signal distortions.

Keywords: switched-mode power amplifier, envelope amplifier, class E, AM/AM, AM/PM, EVM

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НЕЛИНЕЙНЫЕ ИСКАЖЕНИЯ СИГНАЛОВ В УСИЛИТЕЛЯХ МОЩНОСТИ КЛАССА Е, ПРИМЕНЯЕМЫХ В ТРАНСМИТТЕРАХ С ПОЛЯРНОЙ АРХИТЕКТУРОЙ

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Аннотация. Тенденция к повышению энергетической эффективности трансмиттеров, применяемых в системах радиосвязи и телекоммуникаций, фокусирует внимание разработчиков аппаратуры на поиске оптимальных решений при переходе от использования линейных усилителей мощности к усилителям, работающим в ключевом режиме. В работе показано, что при этом необходимо не только оценивать достигаемый выигрыш по КПД, но и учитывать увеличение уровня нелинейных искажений сигналов. Рассмотрены механизмы, приводящие к появлению искажений сигналов в усилителях мощности класса Е, применяемых в трансмиттерах с полярной архитектурой. Показано, что при усилении сигналов с изменяющейся огибающей наиболее заметное влияние на искажение сигналов оказывает паразитный фазовый сдвиг тока в нагрузке усилителя мощности, обусловленный изменением выходной емкости транзистора. Приведены результаты расчетов амплитуды векторной ошибки при использовании многоуровневых спектрально эффективных видов модуляции, в частности квадратурной амплитудной модуляции и амплитудно-фазовой модуляции, которые подтвердили, что фазовые искажения оказывают превалирующее влияние на ухудшение свойств сигналов. Этот вывод подтверждается результатами расчета вероятности битовой ошибки. Показано, что для 16-QAM при BER = 10^{-4} энергетический проигрыш составляет 0,5 дБ, а для 16-APSK его значение увеличивается до 2,2 дБ. Представленные в работе результаты могут быть использованы при разработке методов предыскажений сигналов в ключевых усилителях мощности класса Е, обеспечивающих снижение искажений сигналов.

Ключевые слова: ключевой усилитель мощности, усилитель огибающей, класс Е, AM/AM, AM/PM, амплитуда векторной ошибки

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Introduction

Today the most important tasks for telecommunication and radio systems engineers are data rate and energy efficiency improvement. However, it is challenging to fulfill both of these tasks. To provide data rate improvement, signals with different quadrature amplitude modulation (QAM) types are widely used [1, 6, 13]. These types of signals could be characterized by relatively big constellation size and high spectral efficiency compared to simple analog modulation or manipulation. Despite positive qualities, such signals could be characterized with high dynamic ranges, and high distortion sensitivity. As a result, relatively small nonlinearities in power amplifier (PA) transfer characteristics could cause severe rise in error vector magnitude (EVM) in the transmitter, as well as in bit error rate (BER). These circumstances have led to a significant increase in the requirements for the linearity of PAs.

The use of signals with complicated types of modulation, in addition to increasing the PA linearity, requires its efficiency rising. The main problem here is that amplifying signals with a high peak to average power ratios using linear mode PAs usually decreases the efficiency to 25–30% [2, 3] and this level sufficiently can be increased only by using a switched-mode PA, for example, class E mode [4, 5]. At the same time, it must be remembered that switched-mode PAs are fundamentally nonlinear and its use may be accompanied by an increase in signal distortion.

In well-known publications devoted to the analysis of class E PA characteristics, the authors limit themselves to considering the case of a constant voltage in the transistor supply circuit [4, 5, 7, 8]. The main attention in these works is paid to providing the conditions necessary to eliminate switching losses, for example, switching the transistor at zero voltage at the drain-source terminals (zero voltage switching, ZVS) and zero current in the drain circuit (zero voltage derivative switching, ZVDS). At the same time, it is obvious that the ZVS and ZVDS conditions can only be implemented at a fixed frequency and are extremely sensitive to changes in load and supply voltage: any deviations from the nominal values change the dynamics of the output capacitance charging process, leading not only to an increase in switching power losses, but also to the appearance of amplitude changes which are linear distortions for PA. Moreover, if we consider that the output capacitance of the transistor does not remain constant when the drain voltage changes, as is commonly assumed in well-known class E models, but changes according to a nonlinear law [9], then it is appropriate to assume the appearance of phase distortions of the signals.

The purpose of this work is to study the effect of the nonlinear dependence of the output capacitance of a transistor on the voltage at the drain-source terminals on the distortion of signals with a non-constant envelope in a polar architecture transmitter.

Signal distortion estimation when assuming nonlinear output capacitance in class E PA

It is well-known that in order to amplify signals with a non-constant envelope using a switched-mode PA, the transmitter must be designed in accordance with the polar architecture (Fig. 1). In the RF channel, the amplitude-limited phase-modulated high-frequency signal $S_0(t)$ of the original RF signal $S(t)$, and the envelope channel provides amplification of signal's envelope $S_{env}(t)$, which then enters the power supply chain of the class E PA.

During this work we will assume that the envelope amplifier (EA) does not introduce distortions into the signal and distortions are caused only by the properties of the class E PA. The equivalent circuit of PA, taking into account the specifics of its operation as part of a polar architecture transmitter, is shown in Fig. 2. It has fundamental differences from the well-known class E PA models [4, 5]. As noted above, the voltage in the drain circuit of the transistor is not constant and its behavior can be taken into account using the voltage source $V_{dd}(t)$. With this in mind, the output capacitance of the transistor (the capacitance of the forming contour) is also not fixed and can increase or decrease in accordance with the law of voltage change $V_{dd}(t)$ [9].

The estimation of nonlinear distortions in the class E PA was carried out in two steps. On the first one, according to the diagram in Fig. 2, the voltage $V_{dd}(t)$ was changed and the amplitude and phase of the current in the load were fixed. During this measurement, the phase of the load current at the peak point – when the voltage $V_{dd}(t)$ reaches the maximum value of $V_{dd\,\max}$ and the PA operates in soft switching mode with ZVS and ZVDS conditions – was taken as the initial one. A low-pass filter was used as the load, the parameters of which were determined from the condition for ensuring the frequency overlap coefficient $K_f = f_{\max}/f_{\min} \approx 1.6$ [11]. The evaluation showed that with a decrease in voltage in the range from 1.0 $V_{dd\,\max}$ to 0.1 $V_{dd\,\max}$, the output capacitance of the transistor increases by 3.9 times.

The amplitude (AM/AM) and amplitude-phase (AM/PM) characteristics of the PA depend on the relative voltage $V_{dd\,\max}$ are shown in Figs. 3, 4.

As follows from the analysis of these dependencies, the most noticeable effect of the nonlinearity of the transistor capacitance in a class E PA in a transmitter with a polar architecture is on the

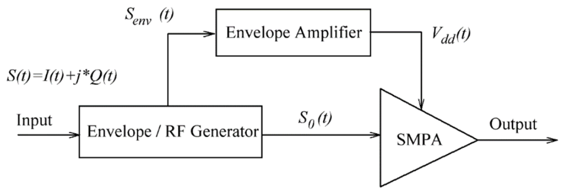

Fig. 1. PA with polar architecture

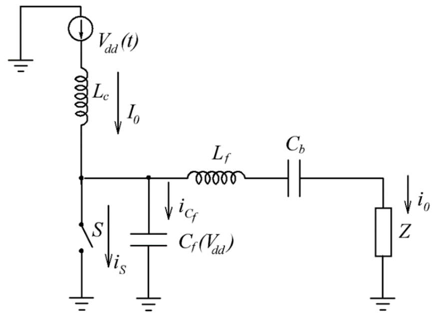

Fig. 2. Equivalent class E schematic

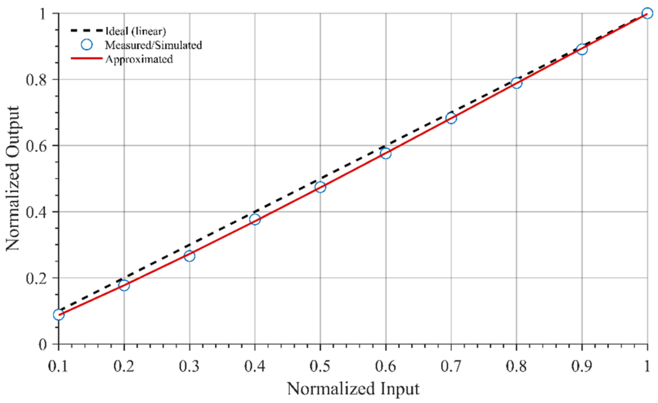

Fig. 3. AM/AM characteristic

amplitude-phase response, leading to a noticeable additional phase shift, which, with the indicated change in the output capacitance of the transistor $C_{max}/C_{min} = 3.9$, reaches 20 degrees.

At the second stage of the research, the EVM was estimated using simulation modeling. During modelling signals with QAM and amplitude-phase shift keying (APSK) were used. These results are shown in Table 1. Here, for comparison, the EVM values, calculated analytically using AM/AM (Fig. 3) and AM/PM (Fig. 4) characteristics are presented.

From the analysis of the results presented in table 1, we can conclude that the difference between the results of the EVM values obtained on the basis of analytical calculations and by simulation modeling does not exceed 1%. Considering that the analytical approach is much simpler to implement, it can be recommended as an estimation of the upper boundary of the EVM value.

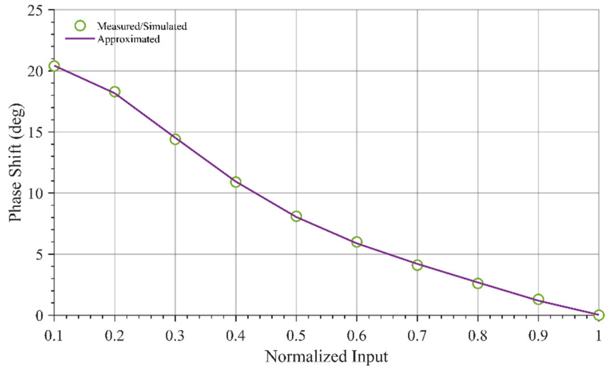

Fig. 4. AM/PM characteristic

a) *b*)

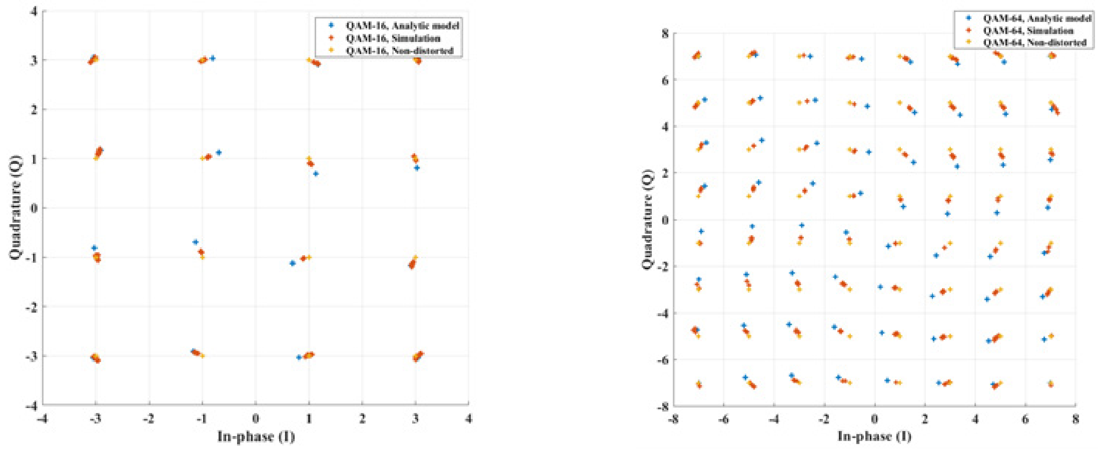

Fig. 5. Constellation diagrams of the PA output signal using different constellation sizes

Table 1

EVM for different modulation types

Modulation	Analytic model, %	Simulation, %
16-QAM	6.77	6.54
64-QAM	8.56	7.89
256-QAM	9.58	8.66
16-APSK	8.15	8.13
64-APSK	8.44	8.67

The impact of nonlinear distortion introduced by the class E PA on the constellation diagram can be evaluated from the positions of the received signal points for 16-QAM and 64-QAM modulated signals. These effects are clearly illustrated in the constellation diagrams presented in Fig. 5, which allow direct visual assessment of the scattering and displacement of the constellation points caused by the amplifier's nonlinear behavior.

Analyzing the relative contribution of amplitude and phase distortions in class E PA to the EVM value, it should be noted that the influence of the second type of distortion is much more noticeable.

a) *b*)

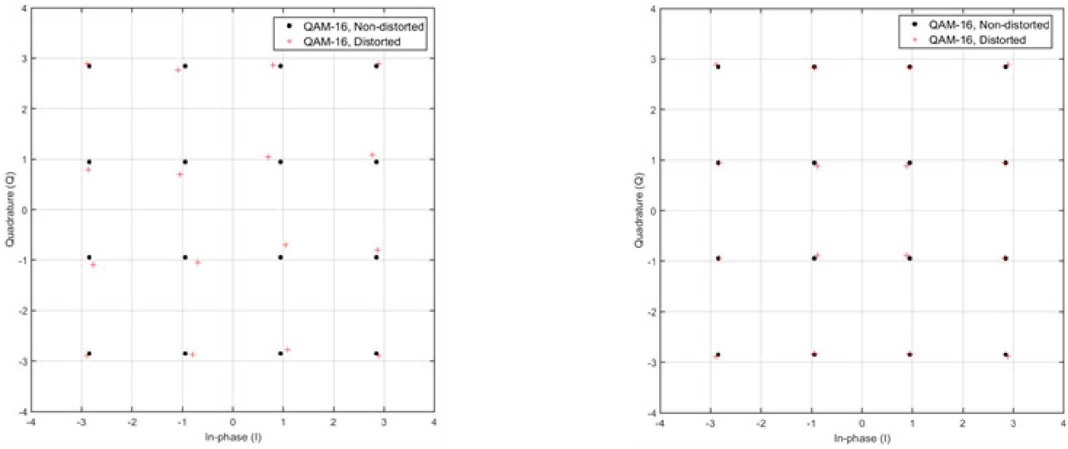

Fig. 6. Constellation diagram for 16-QAM with (*a*) and without (*b*) phase distortion

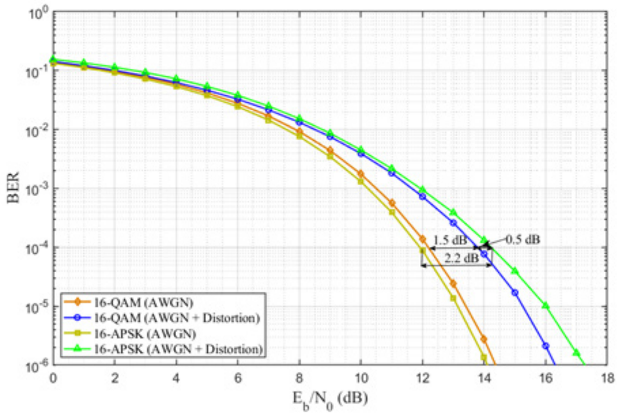

Fig. 7. BER performance of 16-QAM and 16-APSK

This, in particular, can be seen from a comparison of the dependencies in Figs. 3 and 4. A more detailed analysis showed that if it were possible to exclude a parasitic phase shift of the PA output current due to a change in the transistor capacitance, then in this case the EVM would be much smaller and amounted 1.82%. This result is in good agreement with diagrams of constellations shown in Fig. 6 corresponding to 16-QAM in the presence and absence of phase distortions.

Let us evaluate the effect of distortion in Class E PA on the probability of BER depending on the ratio of bit energy to spectral noise density using 16-QAM and 16-APSK signals as examples. The BER performance is evaluted in a channel with additive white Gaussian noise in the presence and absence of nonlinear distortions in the PA (Fig. 7).

From the analysis of the diagrams in Fig. 7, it can be seen that at BER = 10^{-4}, the distortions introduced by the class E PA in the case of signals with 16-QAM lead to an energy loss of 0.5 dB, and with 16-APSK, the loss increases to 2.2 dB. The stronger sensitivity of APSK signals to nonlinear distortions is due to the fundamental structure differences of their constellation's geometry [12], as well as the fact that phase distortions have stronger effect than amplitude ones in class E PA.

Conclusion

Summarizing the results obtained in this paper, we note the following:

1. It is shown that when applying amplifiers operating in switching mode, it is necessary not only to evaluate the efficiency gain achieved in this case, but also to take into account the increase in the level of nonlinear signal distortions.

2. One of the main reasons for the increase in the level of nonlinear distortions in the case of class E PA in a transmitter with a polar architecture is the appearance of a parasitic phase shift of the load current caused by a change in the output capacitance of the transistor when amplifying signals with a non-constant envelope. In particular, it is shown that for the GaN transistor used in the study, the change in the output capacitance of the device can reach 3.9 times, and the parasitic phase shift caused by this effect reaches 20 degrees.

3. Evaluation of the EVM in class E PA based on analytical approach, as well as using simulation modeling, showed that both methods provide approximately the same accuracy, moreover, difference in the EVM value does not exceed 1%. Needless to say, the analytical method is characterized by significantly less labor intensity.

4. When assessing the relative contribution of amplitude and phase distortions to the EVM value, it was found that the second type of distortion is predominant in class E PA. Therefore, in the case of signals with 16-QAM, the presence of amplitude distortion leads to an EVM value of 1.82%, and in the case of simultaneous action of both types of distortion, EVM = 6.77%.

5. The results of evaluating the effect of signal distortion in class E PA on the probability of bit error showed that at BER = 10^{-4} in the case of signals with 16-QAM energy loss is 1.5 dB, and when using 16-APSK signals, the loss increases to 2.2 dB.

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