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CLASS G POWER AMPLIFIER SYNTHESIS BASED ON THE PROBABILITY DENSITY FUNCTION DEPENDENCE OF THE TRANSMITTED SIGNAL

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Abstract. The article describes the technique of parametric synthesis of a class G power amplifier with maximum drain efficiency at the average output power with high PAPR (peak to average power ratio). The proposed technique was applied to an advanced OFDM signal of LTE standard. The optimal parameters of the envelope amplifier for LTE signal were received on the basis of proposed theoretical calculation. Proposed technique validity was confirmed experimentally by measuring the 3-level class G power amplifier prototype. The prototype operates in the frequency range of 700–1000 MHz and has a maximum power 44.3 dBm. It also has a drain efficiency of 30% at power output back-off equal to the peak to average power ratio of LTE signal. From the consistency of the computational and experimental results, it is possible to predict increasing a drain efficiency from 30% to 39.5% by using the digital pre-distortion system and the 5-level envelope amplifier.

Keywords: class G power amplifier, PDF, drain efficiency, OFDM, LTE

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СИНТЕЗ УСИЛИТЕЛЯ МОЩНОСТИ КЛАССА G НА ОСНОВЕ PDF-ЗАВИСИМОСТИ ИЗЛУЧАЕМОГО СИГНАЛА

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Аннотация. Статья посвящена методике параметрического синтеза усилителя мощности класса G с максимальным КПД при средней мощности излучаемого сигнала с высоким пик-фактором. В работе показано применение предложенной методики к передовому OFDM-сигналу стандарта LTE. Получены оптимальные параметры усилителя огибающей в схеме усилителя мощности класса G для LTE-сигнала на основании теоретического расчета. Обоснованность изложенной методики подтверждена экспериментально путем измерения разработанного прототипа усилителя мощности класса G с тремя уровнями коммутации напряжения питания. Прототип работает в частотном диапазоне 700–1000 МГц, имеет максимальную мощность 44,3 дБм и КПД 30% при отстройке от максимальной мощности на величину пик-фактора LTE-сигнала. Из согласованности результатов расчет и эксперимента возможно предсказать, что при использовании системы предыскажений и усилителя огибающей с пятью уровнями коммутации напряжения питания КПД возможно увеличить с 30% до значения 39,5%.

Ключевые слова: усилитель мощности класса G, PDF, КПД, OFDM, LTE

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Introduction

The problem of designing power amplifier (PA) with high efficiency for signals with high peak to average power ratio (PAPR) exists for a long time. Linearity and efficiency are trade-off parameters in PA design. The rapid digital electronics development has enabled implementation of the digital pre-distortion (DPD) system, which in turn has changed the trade-off between linearity and efficiency towards high efficiency. With the advent of DPD systems it becomes possible to use such PAs as the Doherty amplifier.

Doherty amplifier or other PAs with load modulation technique [1, 2] can be realized in a narrow frequency rang. PA with a supply modulation technique such as envelope tracking power amplifier (ET-PA) [3, 4] is the most interesting solution for high bandwidth task. A special case of ETPA is a class G PA [5, 6] that has a supply modulation between discreet levels. The class G PA has high efficiency of the envelope amplifier, because it works in a pulse mode.

Now, there are some scientific articles describing class G PAs with 2, 3 or 8 supply levels [5, 6]. However, the task of determining the optimal parameters for maximum efficiency at average signal power is steel open. This work is a continuation of work [7] proposing the class G power amplifier synthesis based on a transmitted signal complementary cumulative distribution function (CCDF). Further development of this synthesis technique described in this work has determined the final theoretical basis used a probability density function (PDF) for the parametric synthesis of a class G PA, confirmed by experiment.

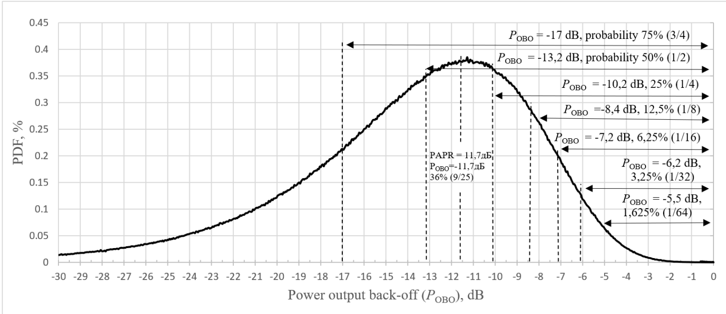

Fig. 1. PDF for LTE signal

PDF analyses

Work [7] shows that class G PA efficiency must be calculated using PDF and measurements of the main PA at discrete supply voltages. PDF determines the detecting probability of particular supply voltage level. For probability analysis, two functions are most often used: PDF and CCDF. CCDF doesn't have information about the detecting probability for signal with power less than average level. The proposed CCDF-based efficiency analysis technique [7] isn't able to determine the maximum efficiency at PA parameters that depends on the integral probability.

Fig. 1 shows probability function for the OFDM signal of LTE standard E-TM3.1 test configuration.

In order for the efficiency synthesis technique to be independent of parameters of the main PA, it is advisable to normalize the output power by maximum PA power. This normalized value is called "the power output back-off" (P_{OBO}). Integrating the PDF in specified intervals gives the opportunity to determine the probability density of signal power occurring in the selected interval.

Let us suppose that the class G PA has two switching supply voltage levels U_1 and U_2. The supply voltage will able to change by using a comparator. The comparator will change the supply voltage when power exceed some reference value (P_{REF}). Let P_{REF} correspond to P_{OBO} = –11.7 dB then, according to Fig. 1, the main amplifier will be at U_1 74% of time, and at U_2 – 36% of time. It is better to select U_1 and U_2 values at which the main PA will provide the required maximum powers for the given P_{OBO} intervals. Measuring the efficiency of the main PA for the found supply voltages allows to determine the drain efficiency (DE) of the overall class G PA using the following formula:

$$\mathrm{DE}(\%) = 100\%\Big(p(U_1)\,\mathrm{DE}\big(P_{\mathrm{avg1}}(W), U_1\big) + p(U_2)\,\mathrm{DE}\big(P_{\mathrm{avg2}}(W), U_2\big)\Big), \tag{1}$$

where $p(U_N)$ is integral probability in a given interval corresponding to the supply voltage U_N; DE (P_{avgN}, U_N) is measurements of the drain efficiency of the main PA for P_{avgN}, given in Watts, and corresponding to the supply voltage U_N. In its turn, the average power for a certain interval can be calculated using the next formula:

$$P_{\mathrm{avgN}}(W) = \frac{\sum_{i=N_k}^{N_m} 0.001W \cdot 10^{\frac{P_M(dBm)+P_{\mathrm{OBO}_i}(dB)}{10}}\,\mathrm{PDF}\big(P_{\mathrm{OBO}_i}\big)}{\sum_{i=N_k}^{N_m}\mathrm{PDF}\big(P_{\mathrm{OBO}_i}\big)}, \tag{2}$$

where P_M is instantaneous power obtained as a result of the reverse transition from the normalized P_{OBO} value to the output signal power; PDF(P_{OBO}) is PDF value at P_{OBO_i}; [U_k, U_m] is interval with constant supply voltage U_N.

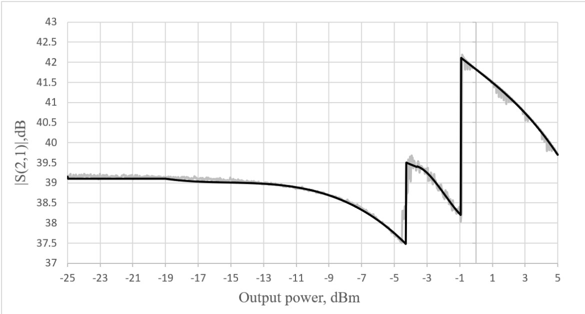

Fig. 2. Gain module

Calculating the efficiency at an average signal power allows to select such PA parameters at which the maximum efficiency value can be achieved. These parameters include: the integral probability ($p(U_N)$), which is determined by the reference voltage of the comparators; N-level supply voltage (U_N); the number of supply voltage levels (N).

Let us analyze the DE for the main PA made on LDMOS technology with a maximum power of 47 dBm at a supply voltage of 28 V. The number of supply voltage levels $N = 5$ is the optimal value for LTE signal, because the DE of class G PA is close to the maximum value 44.5% achieving in ETPA. The optimal parameters of a class G PA with five supply voltage levels are shown in Table 1.

Table 1

The optimal envelop amplifier parameters

Level number (N)	1	2	3	4	5
U_N, %	6.5	7.5	10.6	13.5	28
$p(U_N)$, %	50	14	29.7	4.7	1.6
P_{avgN}N, dBm	30.3	34.6	37	37.3	42
DE(P_{avgN}, U_N), %	39	47	49	48	38

Note, that it is needed to use the PDF of the output signal for analysis. The PA is a nonlinear element, therefore, without a DPD system, the output signal has distortion. The PDF will be curved in this case, so this technique is applicable only with DPD system.

Class G PA distortion analyses

Fig. 2 and 3 show the measuring results of a complex transfer function for the 3-level class G PA prototype, developed in [7], and matched in 700–1000 MHz frequency range with a maximum output power of 44.3 dBm at a supply voltage 28 V.

Fig. 2 and 3 show the measurement results approximated by a piecewise polynomial sequence. When the supply voltage changes, the transfer function is discontinuing and, therefore, cannot be approximated by Taylor series. Accordingly, the transfer function of a Volterra series of DPD system is not suitable for class G PA. Today, there are some works [8, 9] describing the implementation of DPD technique for class G PA.

Based on the piecewise polynomial approximation data, a model of PA prototype was built in the VSS AWR software environment and PDF of output signal was analyzed. Fig. 4 shows the probability function for an average signal power of 33 dBm.

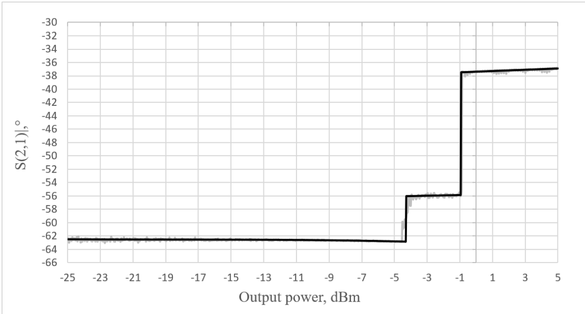

Fig. 3. Gain phase

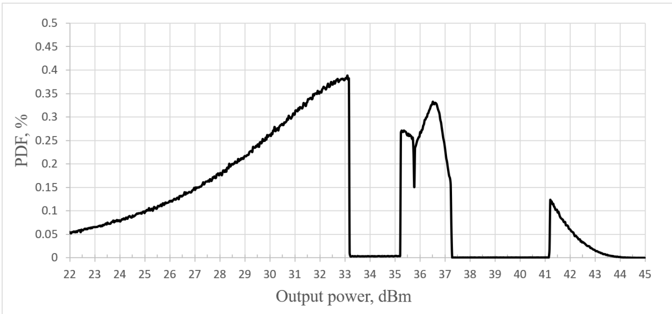

Fig. 4. PDF for P_{avg} = 33 dBm

The PDF has areas where the PDF is zero, because the power gain increases sharply when supply voltage changes. There is also distortion in the graph caused by gain compression at each supply voltage.

Class G PA is an element with a high level of nonlinear distortion. The ACPR of 33 dBm output signal is –22 dBc. However, all amplifier architectures solving the problem of low DE at signals with high PAPR need to correct additional DPD technique. For example, LTE standard has ACPR requirement less that –50 dBc. Table 2 provides the typical ACPR and DE for popular PA architectures.

Table 2

Parameters of different PA architectures

PA architectures	ACPR, dBc	DE, %	References
Doherty PA	–30 ÷ –35	35 – 60	[1, 2]
ETPA	–32 ÷ –40	26 – 40	[3, 4]
Class G PA	–20 ÷ –25	38 – 43	[5, 6]
Class G PA	–22	44.3	this work

Prototype measurements results

Optimal parameters for achieving maximum efficiency for P_{avg} = 32.5 dBm were calculated. At this moment, DPD system is not developed, therefore, we use PDF for output signal with distortion for DE analyzation. A comparison of the measurement and calculation results is shown in Fig. 5.

A comparison of the calculation and experimental results shows that at an output power of 30.5 dBm and above, the measured efficiency value approaches the calculated one, which indicates the

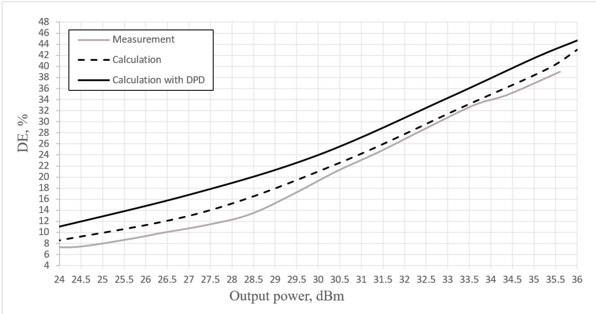

Fig. 5. Measurement results

high efficiency of the envelope amplifier in the prototype. In this output power range, the supply voltage begins to switch between three levels, while at a power below 30.5 dBm only supply voltage U_1 prevails. The current in U_1 circuit flows through the diode with the drop voltage by 0.77 V, which leads to efficiency decreasing of the envelope amplifier.

Fig. 5 also shows the dependence of the possible DE of the prototype with the DPD system. Calculations show that DPD system can increase the efficiency by 3%. It is possible to predict that the DE of the class G prototype for the number of switching levels (N) is 5. Finally, with $N = 5$ and using a DPD system, the prototype will have expected DE equal to 39.5%.

Conclusion

The class G PA is a relevant solution for the problem of PA synthesizing in a wide operating frequencies range. The technique presented in this work allows synthesize a class G PA with maximum efficiency for signals with the certain structure. This article shows that synthesis of 5-levels class G PA for advanced OFDM signals is optimal.

At the moment, a search of DPD system design technique for class G PA is still ongoing. Also, it is relevant to implement the envelope amplifier in an integrated design for improving the frequency properties and reducing the response time.

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