ADVANCED DESIGN TECHNIQUES FOR RF POWER AMPLIFIERS

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ADVANCED DESIGN TECHNIQUES FOR RF POWER AMPLIFIERS

by

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Springer

A C.I.P. Catalogue record for this book is available from the Library of Congress.

ISBN-10 1-4020-4638-3 (HB)
ISBN-13 978-1-4020-4638-4 (HB)
ISBN-10 1-4020-4639-1 (e-book)
ISBN-13 978-1-4020-4639-1 (e-book)

Published by Springer,
P.O. Box 17, 3300 AA Dordrecht, The Netherlands.

www.springer.com

Printed on acid-free paper

Printed in the Netherlands.

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Preface

Power amplifier is the main power consumption block in any advanced wireless communications system. When the DC power is limited, it is crucial to design power amplifiers with high power-added efficiency. The output power and efficiency depends on the active device, bias conditions according to the operating class, matching networks, and so on. One of the methods to improve the output power and efficiency is to terminate the harmonics at the output. Among the harmonics, the first five are especially in want of tuning, because their magnitudes are relatively larger than the others'.

In the last seven years the authors have made a lot of efforts in the field of development of high-efficiency polyharmonic power amplifiers, and the original results are highly enhanced both by the modelling and the related design methodologies. Thus, the main idea of this book will be to provide the reader with a deep analysis of modeling and design strategies of BJT high-efficiency polyharmonic power amplifiers, as well as to organize in a coherent manner all the authors' results in the field of polyharmonic power amplifiers. Hence, the book allows the reader not only to understand the operating principle and the features of bipolar transistor power amplifiers, but also to design high-efficiency amplifiers at the frequencies close to transition.

The book can be used as a guide by researchers and practicing engineers dealing with this subject and as a text book to graduate and postgraduate students who want to extend their knowledge and study all aspects of the analysis and design of high-efficiency polyharmonic power amplifiers. Although the material is presented in a formal and theoretical manner, much emphasis is made on a design perspective. To further link the book's theoretical aspects with practical issues, simulation and experimental examples are included.

The book is organized into five chapters. Chapter 1 is introductory and it contains analytical review of current state of high-efficiency power amplifiers design problem. The strength and weakness of existing approaches are highlighted, unsolved issues pointed out.

Chapter 2 of the book is devoted to theoretical analysis of BJT class-F power amplifier near transition frequency and is divided into three sections. In section 1, we propose the simplified transistor model accounting the charge storage issues that will be needed in the sequel. Section 2 describes the analytical derivation of collector current harmonic content depending on the operating frequency and the biasing conditions, while section 3 presents the Class F realization conditions according to the analysis.

Chapter 3 deals with verification and demonstration of the results achieved in Chapter 2. Section 1 covers the simulation of BJT class-F power amplifier near the transition frequency using the accurate transistor model. Furthermore, section 2 contains experimental results of the fabricated prototype.

Chapter 4 is devoted to the use of photonic band-gap structures (PBG) as the output networks of high-efficiency polyharmonic power amplifiers. The novel type of PBG is proposed providing improved characteristics in the both stop and pass bands.

Finally, Chapter 5 presents the BJT fifth-harmonic peaking class F power amplifier design using proposed in Chapter 4 structure.

In addition, we provide our own comprehensive nonlinear power amplifiers' simulation tutorial in Appendix.

Anna Rudiakova,

Vladimir Krizhanovski

Chapter 1

INTRODUCTION TO THE RF POWER AMPLIFIERS DESIGN

1. BASIC TERMS AND DEFINITIONS

The general equivalent circuit of power amplifier is shown in Fig. 1-1. It consists of active device (AD), input and output networks and supply and bias circuits[1,2].

Electrical operation mode of power amplifier can be characterized by the following fundamental parameters: the first harmonic output power P_1, the dc supply power P_{DC}, the efficiency regarding the first harmonic $\eta = P_1/P_{DC}$ (so-called electronic efficiency), the power gain K_P, the pass-band or amplitude-frequency characteristic, and the nonlinear distortions values. The power-added efficiency (PAE) is also important characteristic accounting the driving signal power.

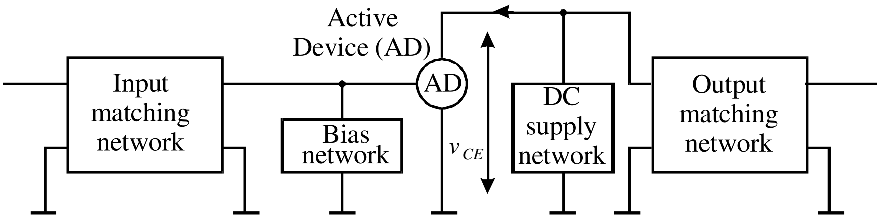


Figure 1-1. General equivalent circuit of power amplifier.

The driving signal source and supply voltage source parameters substantially influence the power amplifier operation. These external parameters are the following:

- nominal power P_{in}, frequency f and intrinsic impedance Z_i of the driving signal source;

- voltage E_C of supply voltage source, and the load impedance Z_L at the transistor output terminals.

The dependencies of the amplifier parameters on the external parameters present the sets of characteristics as follows:

- load: dependencies of P_1, P_{DC}, η, K_P on the load impedance Z_L;
- amplitude: dependencies of P_1, P_{DC}, η, K_P on the input power P_{in};
- modulation: dependencies of P_1, P_{DC}, η, K_P on the supply voltage E_C;
- frequency: dependencies of P_1, P_{DC}, η, K_P on the driving signal frequency.

The approximate views of the load, amplitude, modulation, and frequency characteristics' sets are shown in Figs. 1-2 - 1-5, respectively. The $f_1 < f_2 < f_3$ is assumed for all of the figures.

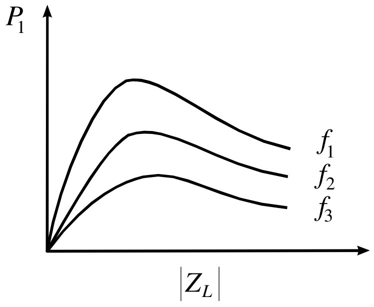


Figure 1-2. Load characteristics' set.

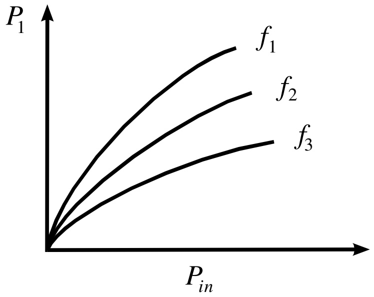


Figure 1-3. Amplitude characteristics' set.

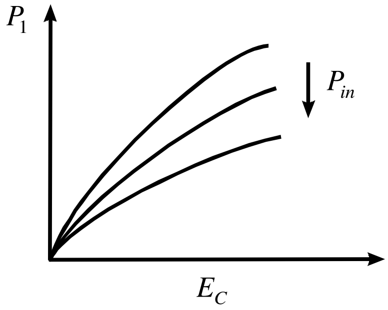


Figure 1-4. Modulation characteristics' set.

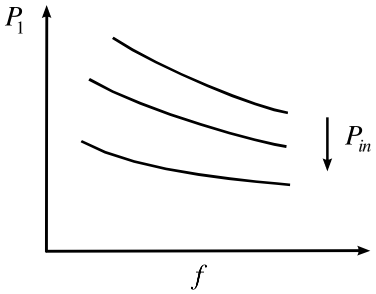


Figure 1-5. Frequency characteristics' set.

There are other characteristics' sets besides the above mentioned: for example, the bias characteristics, etc. However, the above four sets are of special importance.

The nonlinear power amplifier can operate in one of the following modes: undersaturated, critical, overloaded, switching. The latter two belong to the saturated one.

The amplifier's operating mode can be determined by the dynamic load line, which represents the operating point coordinates at the current-voltage curves' plane. The mode is undersaturated, if the dynamic load line stays within the active and cut-off regions as shown in Fig. 1-6. However, when it moves to the saturation region, the operating mode becomes overloaded. The critical mode is the boundary between the undersaturated and overloaded ones. In this case, the operating point is just touching the saturation line.

The switching mode assumes the transistor as an ideal switch that can be either in the saturation region, or in cut-off. This mode can be considered as an extreme case of overloaded one.

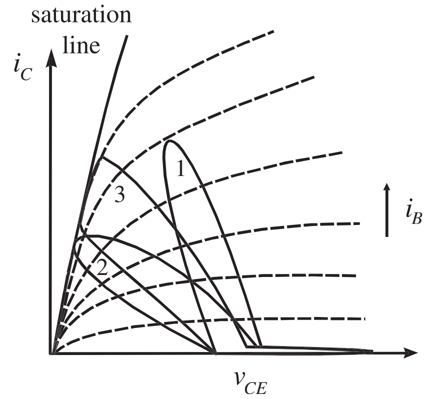


Figure 1-6. Dynamic load lines for the undersaturated (1), critical (2), and overloaded (3) operating modes.

The power amplifiers are divided into several classes within two major groups depending on the input signal amplitude, bias and supply conditions, and the properties of the input and output matching networks: 1) the sine-wave output operation, and 2) the polyharmonic operation. The detailed description of these classes is given in the further paragraphs.

2. SINE-WAVE OUTPUT OPERATION: CLASSES A, AB, B, C

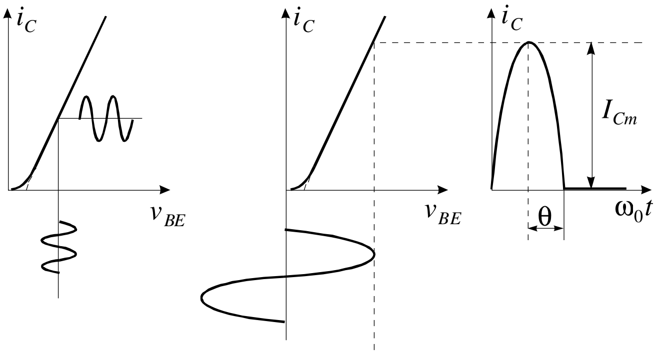
There are two cases for the sine-wave output operation power amplifiers as shown in Fig. 1-7: 1) the small signal class A - linear mode, and 2) the large signal modes with cut-off.

The magnitude of RF signal is much smaller than its dc component for the linear mode (see Fig. 1-7 (a)). Typical application of such amplifiers is the input low-power stages of RF transmitters. Maximal theoretically reachable efficiency is equal 50% for this case.

The large-signal operation modes (see Fig. 1-7 (b)) give the advantage of higher efficiency. Here, the collector current is zero during the cut-off interval, so the instant parasitic power dissipation becomes zero for this region leading to the efficiency increasing.

The large signal operation modes are divided into different classes according to the conduction angle as follows: class AB with $90° < \theta < 180°$, class B with $\theta = 90°$, and class C with $\theta < 90°$.

The analytical expression for the large-signal operation collector current i_C is following:



(a) (b)

Figure 1-7. Small signal class A operation - linear mode (a), and large signal nonlinear modes with cut-off (b).

$$\left.\begin{aligned} i_C = I_{Cm}\frac{\cos\omega t - \cos\theta}{1-\cos\theta}, \text{for} -\theta < \omega t < \theta \\ i_C = 0, \text{for}\ \theta < \omega t < 2\pi - \theta \end{aligned}\right\}, \tag{1-1}$$

where I_{Cm} is the maximal collector current value, θ is the conduction angle, which is equal to the half of nonzero current interval, and varies from 0° to 180°.

The dependencies of the Fourier coefficients α_0 and α_1 of the collector current dc component $I_{C0} = I_{Cm}\alpha_0$ and fundamental frequency component $I_{C1} = I_{Cm}\alpha_1$ on θ are the following:

$$\alpha_0 = \frac{\sin\theta - \theta\cos\theta}{\pi(1-\cos\theta)}, \quad \alpha_1 = \frac{\theta - \sin\theta\cos\theta}{\pi(1-\cos\theta)} \tag{1-2}$$

In case of higher harmonics, the appropriate Fourier coefficients should be determined as:

$$\alpha_n = \frac{2}{\pi}\frac{\sin n\theta\cos\theta - n\cos n\theta\sin\theta}{n(n^2-1)(1-\cos\theta)}, \quad n \geq 2$$

The α_0 - α_3 coefficients are shown in Fig. 1-8.

Assuming the ideal matching and harmonic output voltage, the collector efficiency can be written as:

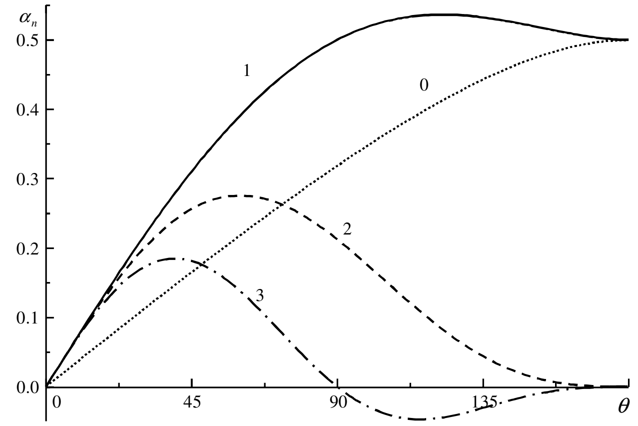


Figure 1-8. The dependencies of the Fourier coefficients α_0 - α_3 on θ.

$$\eta = \frac{P_1}{P_{DC}} = \frac{1}{2}\frac{I_{C1}V_{C1}}{I_{C0}E_C} = \frac{1}{2}\xi\frac{\alpha_1}{\alpha_0}, \tag{1-3}$$

where the $\xi = V_{C1}/E_C$ is the transistor utilization factor, $\xi \le 1$. As it is follows from Eqs. (1-2) and (1-3), the efficiency increases when the conduction angle decreases. Furthermore, the efficiency approaches 100% for the $\theta \to 0$ and $\xi = 1$.

As the collector current becomes almost zero during the cut-off interval, the dissipated power is smaller for the decreased conduction angle. However, the fundamental component power goes down dramatically for a low θ. That is why the class B or class C with θ greater than 60° are usually used. It allows obtaining $\eta = 70..80\%$ and acceptable output power level[3-7].

3. POLYHARMONIC OPERATION: CLASS F

The polyharmonic operation is characterized by the complex output voltage waveform[8], which contains the series of harmonics. In general case, the output voltage includes infinite number of harmonics:

$$v_C = E_C - \sum_{n=1}^{\infty} V_{Cn}\cos(n\omega t + \varphi_n),$$

However, only few first harmonics are considered practically.