PHASE TUNING APPROACH FOR POLYHARMONIC POWER AMPLIFIERS

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ABSTRACT

In this paper, new conditions for achieving the high efficiency and high output power capability of polyharmonic power amplifies are presented. These conditions can be used in future development of new types of polyharmonic amplifiers with similar efficiency and output power capability as those of Class F amplifies. However, a quite difficult tuning of an output network as in class-F amplifiers is not required.

INTRODUCTION

Polyharmonic operation of power amplifiers relies on the use of a special input drive signal and harmonic tuning of input and output networks in order to improve basic amplifier's characteristics such as efficiency, output power capability and linearity. It is a more popular and widely used approach. However, as was mentioned by Raab (1), this method is also least understood.

The first descriptions of the class-F power amplifiers concept were made by Tyler (2), and Snider (3). In these publications, a special tuning of an output network was used to control the *n* input impedance of the output network at the carrier frequency harmonics. A short circuit is provided for an active device output at the even harmonic frequencies, and an open circuit is provided at the odd harmonic frequencies. In (4), Raab proposed to use the term "class-F" for such a type of harmonic tuning.

Strong dependence of proper tuning of class-F amplifiers on an input bias condition, which determines an active device conduction angle, was demonstrated by Colantonio et al (5). It was shown that class-F operation is possible using class-AB biasing conditions, resulting in the conduction angle above 180°, but this lead to additional efficiency loss. Many researchers have applied the concept of class-F operation (e.g., Toyoda (6), and Ingruber et al (7)). However, the majority of previous papers were experimental, and a unified theory for amplifiers with polyharmonic operation has not still been developed.

The objective of this paper is to introduce new condition for achieving high efficiency and high output power capability of polyharmonic amplifiers.

IMPROVING HIGH OUTPUT POWER CAPABILITY

A general block diagram of a high-frequency power amplifier is shown in Fig. 1. It consists of an active device (a MOSFET, a MESFET, a bipolar transistor, a vacuum tube, etc.), an input network including an input drive circuit, an output network including a dc supply circuit, and a resistive load. A reactive part of the load (if any), may be included in the output matching network. In case of polyharmonic amplifier operation, the output network should provide special impedance to the high-frequency harmonic components. It is assumed that only fundamental harmonic component reaches the load, and input and output networks are lossless.

The power dissipated in an active device (neglecting the transistor drive power) is $P_D = \frac{1}{T}\int_{-T/2}^{T/2} v_{DS} i_D dt$, which can be expressed using the spectral components of the v_{DS} and i_D waveforms as follows:

$$P_D = \frac{V_m I_m}{T}\int_{-T/2}^{T/2}\sum_{n=0}^{\infty}\alpha_n\cos(n\omega t+\varphi_n)\sum_{l=0}^{\infty}\beta_k\cos(k\omega t+\psi_k)dt\ . \qquad (1)$$

Here V_m and I_m are the maximum values of the drain voltage and current, and α_n, φ_n, β_k, and ψ_k are the Fourier coefficients of the current and voltage, respectively. Integration of eqn (1) (taking into account the fact that the voltage and current waveforms at an active device output are in anti-phase) yields

$$P_D = V_{DD} I_{DD} - V_m I_m \frac{\alpha_1 \beta_1}{2} \cos(\varphi_1 - \psi_1) - V_m I_m \sum_{n=2}^{\infty} \frac{\alpha_n \beta_n}{2} \cos(\varphi_n - \psi_n) \qquad (2)$$

where V_{DD} and I_{DD} are the dc components of drain voltage and current, respectively. Assuming the exact matching of the fundamental component with load, one obtains

$$P_D = V_{DD} I_{DD} - V_m I_m \frac{\alpha_1 \beta_1}{2} - V_m I_m \sum_{n=2}^{\infty} \frac{\alpha_n \beta_n}{2} \cos(\varphi_n - \psi_n) \qquad (3)$$

where $V_{DD} I_{DD} = P_{DD}$ is the dc supply power, and $U_m I_m \frac{\alpha_1 \beta_1}{2} = P_1$ is the output power at the fundamental frequency. Substitution of these into eqn (3) gives

$$P_D = P_{DD} - P_1 - \frac{V_{DSm} I_{Dm}}{2} \sum_{n=2}^{\infty} \alpha_n \beta_n \cos(\varphi_n - \psi_n) \ . \qquad (4)$$

Thus, the output power at the fundamental frequency P_1 is

$$P_1 = P_{DD} - \frac{V_{DSm} I_{Dm}}{2} \sum_{n=2}^{\infty} \alpha_n \beta_n \cos(\varphi_n - \psi_n) - P_D \ . \qquad (5)$$

As can be seen from eqn (5), the second term should be decreased in order to obtain the highest output power at a given P_{DD}. In case of polyharmonic operation, the maximum value of P_1 with a quite low P_D, P_1 approaches P_{DD}. This can be realized if either the current or voltage, but no both, are present at any higher harmonic frequency, i.e., if either α_n or β_n**,** but not both, are simultaneously zero. These are the conditions for the class-F operation. But as can be seen from eqn (5), it is not unique way. The second term on the right-hand side of eqn (5) depends also on the phase shift between the output current and voltage at higher harmonic frequencies. If the phase difference $\varphi_n - \psi_n$ is $\pm\pi/2$ for all pairs of current and voltage harmonics of the same order, the second term in eqn (5) is also zero. Such the condition is new and do not appropriate to any of existence polyharmonic classes. It can be realized by providing a reactive impedance of the output network at higher harmonic frequencies. In the previous literature, the condition was not reported. It could lead to future designs of new types of polyharmonic amplifiers with similar efficiency and output power capability as those in class-F amplifiers, but it does not require a quite difficult tuning of the output network as class-F amplifiers.

ACHIEVING HIGH EFFICIENCY

The general expression for the drain efficiency of power amplifiers is

$$\eta_D = \frac{P_1}{P_{DD}} \ . \qquad (6)$$

Suppose that the phase shifts at higher harmonics satisfy the condition obtained in above Section, obtains:

$$\eta_D = \frac{P_{DD} - P_D}{P_{DD}} \ . \qquad (7)$$

In order to achieve high efficiency, P_D should be decreased. One way to reduce P_D is non-simultaneous existence of substantial current and voltage at a transistor output. This is the condition for high-efficiency amplifier operation. At high frequencies, the operating frequency can be close to the transition frequency of an active device. In this case, the output current of an active device can be negative during a part of the ac cycle due the strong influence of the currents through the transistor capacitances. Taking into account the fact that the output voltage is always positive, the instantaneous transistor power loss has negative values during a part of the high-frequency cycle. Therefore, the transistor average power dissipation P_D decreases, yielding high efficiency. In order to show the effect of negative collector current on the power amplifier efficiency, let us assume sinusoidal collector-emitter voltage and collector current as follows:

$$v_{DS} = V_{DD} - V_m \sin\omega t\,,\quad V_{DD} < V_m \tag{8}$$

$$i_D = I_{DD} + I_m \sin(\omega t + \varphi),\quad 0 < I_{DD} < I_m \tag{9}$$

In this case, v_{DD} is always positive, and i_D takes on negative values during a part of the ac cycle. From the eqns (8) and (9), the average power dissipated in a transistor is given by

$$P_D = I_{DD}V_{DD} - \frac{1}{2} I_m V_m \cos\varphi\,. \tag{10}$$

There are three possible cases for eqn (10) according with eqn (8) and eqn (9).

Case I: $P_D > 0$ at $\varphi = 0$, which gives

$$I_{DD}V_{DD} > \frac{1}{2} I_m V_m\,. \tag{11}$$

Case II: $P_D = 0$ at $\varphi = 0$, which produces

$$I_{DD}V_{DD} = \frac{1}{2} I_m V_m\,. \tag{12}$$

Case III: $P_D < 0$ at $\varphi = 0$, which gives

$$I_{DD}V_{DD} < \frac{1}{2} I_m V_m\,. \tag{13}$$

According to the energy conservation law, negative values of P_D are physically impossible. Hence, from eqn (10), one obtains $P_D \geq 0$ when

$$\cos\varphi \leq \frac{2I_{DD}V_{DD}}{I_m V_m}\,. \tag{14}$$

Therefore, the phase angle φ must be in the following ranges:

$$-\frac{\pi}{2} \leq \varphi \leq \arccos\left(\frac{2I_{DD}V_{DD}}{I_m V_m}\right) \tag{15}$$

or

$$\arccos\left(\frac{2I_{DD}V_{DD}}{I_m V_m}\right) \leq \varphi \leq \frac{\pi}{2}\,. \tag{16}$$

However in general, due to the presence of resistive elements of active device, the overall power dissipated in a transistor is always positive and has some non-zero minimum.

CONCLUSIONS

In this paper, the output power capability and efficiency of high-frequency power amplifiers were studied using spectral components of the output current and voltage waveforms at an active device, taking into account the phase shift between the higher harmonics. The new conditions for achieving high output power capability and high efficiency were derived. The conditions can lead to future developing of a new class of polyharmonic amplifiers with similar to efficiency and output power capability as those in class-F amplifiers, but a quite difficult tuning of the output network is not required as in class-F amplifier.

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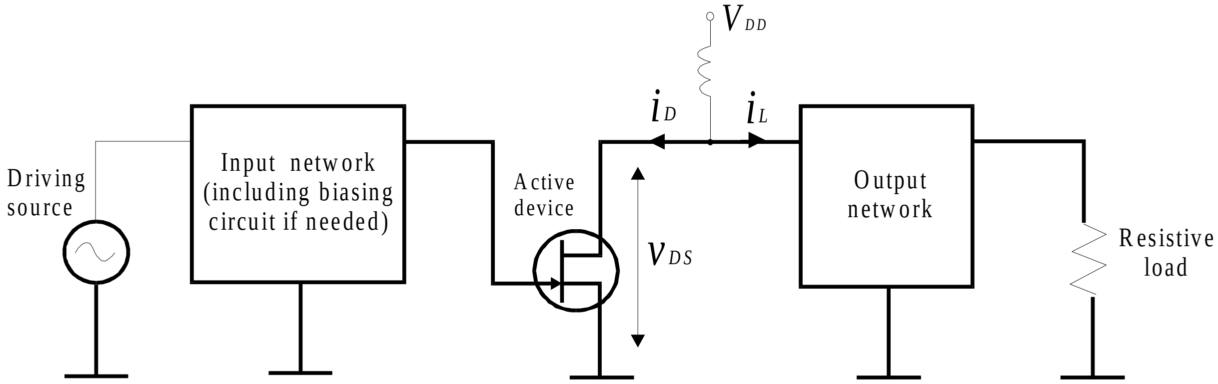

Figure1. General block diagram of a high-frequency power amplifier.