SWITCHED-MODE TUNED HIGH-EFFICIENCY POWER AMPLIFIERS: HISTORICAL ASPECT AND FUTURE PROSPECT

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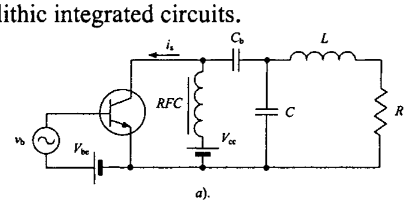
Abstract - **In this paper, an analytical overview of theory and practice of the switched-mode RF and microwave tuned Class E power amplifiers are presented. Well-known and unknown different circuit configurations, equation-based parameters and waveforms are given and discussed.**

I. INTRODUCTION

The switched-mode tuned power amplifiers are widely used in different frequency ranges and output power levels beginning from several kilowatts at low RF frequencies and up to about one watt at microwaves. In these power amplifiers, the transistor operates as an on-to-off switch and the shapes of the current and voltage waveforms provide a condition when the high current and high voltage do not overlap simultaneously that minimize the power dissipation and maximize the power amplifier efficiency. Such an operation mode can be realized for the tuned power amplifier by an appropriate choice of the values of the reactive elements in its output load network, which should be mistuned at the fundamental frequency. Consider the main achievements in the switched-mode tuned power amplifier design in their historical retrospective. For the first time, a possibility to increase the efficiency of the single-ended power amplifier by mistuning of the output matching circuit was experimentally described by Lohrman in 1966 [1]. Three years later, Artym [2] and Gruzdev [3] presented the theoretical analysis of the operation conditions of the single-ended switched-mode power amplifiers with the calculation of their circuit parameters. At that, the analysis was done not only for the switched-mode power amplifier with the shunt capacitance but also using the second resonant circuit tuned on the fundamental to provide the sinusoidal signal flowing into the load [2]. Then, the generalized analysis of the electrical performance and circuit parameters of the single-ended switched-mode power amplifiers with shunt capacitance C and series inductance L shown in Figure 1(a) and with parallel LC circuit shown in Figure 1(b) was given by Popov [4] and Kozyrev [5]. Unfortunately, all these analytical papers were written in Russian in non-translated journals so that they were practically unacceptable for wide world using. However, up to now these results represent a great interest as containing some interesting theoretical results and practical circuit configurations, which can be used successfully for modern RF and microwave switched-mode high-efficiency power amplifiers implemented in hybrid or monolithic integrated circuits.



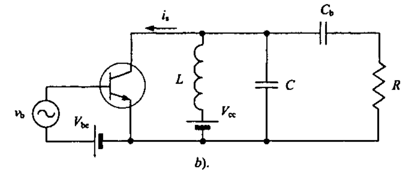


Fig. 1. Single-ended switching power amplifiers with (a) shunt capacitance and series inductance and (b) parallel circuit

II. CLASS E WITH SHUNT CAPACITANCE

The single-ended switched-mode power amplifier with a shunt capacitance as a Class E power amplifier was introduced by Sokals in 1975 and has found widespread application due to their design simplicity and high efficiency operation [6]. In the simplest case, the load network can be represented by the shunt capacitance C and inductance L connected in series with the load R [3, 4]. The collector of the transistor is connected to the supply voltage by the choke inductance with high reactance at the fundamental frequency. The active device is considered to be an ideal switch that is driven in such a way in order to provide the device switching between its on-state and of-state operation conditions. For lossless operation mode, it is necessary to provide the following optimum conditions for voltage across the switch just prior to the start of switch on at the moment $t = T$, when transistor is saturated:

$$v_s(t)\big|_{t=T} = 0 \qquad \left.\frac{dv_s(t)}{dt}\right|_{t=T} = 0$$

where T is the period of input driving signal, v_s is the voltage across the switch. The circuit analysis for a 50% duty cycle gives the following optimum parameters:

$$R = 0.35\frac{V_{cc}^2}{P_{out}}, \quad L = 1.75\frac{R}{\omega}, \quad C = \frac{1}{4.5\,\omega R},$$

where $P_{out} = I_0 V_{cc}$ is the output power at the idealized lossless operation conditions [3]. However, to provide an idealized switched operation mode the loaded quality factor of this L-type circuit should be sufficiently small. As a result, the level of harmonic components flowing onto the load is too high, of about 5-15% [4, 5].

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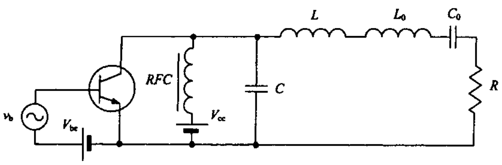

Fig. 2. Class E power amplifier with series LC-filter

For additional harmonic suppression, it is necessary to connect the load through the series filtering circuit tuned on the fundamental, for example, a simple LC-filter shown in Figure 2. Let the moments of switch-on τ_1 and switch-off τ_2 with period of repeatability 2π are determined by the input circuit of the power amplifier, and switch is closed during the time period $\Delta\tau = \tau_2 - \tau_1$, where $\tau = \omega t$. In Figure 3, the voltage and current waveforms for optimum Class E operation with shunt capacitance are shown [5]. The theoretical analysis of such a Class E power amplifier with shunt capacitance, but from another starting point, was also done by Raab [7] assuming the sinusoidal output current to be

$$i_R(\omega t) = I_R \sin(\omega t + \varphi),$$

where φ is the initial phase shift. Then, the optimum parameters of the load network were determined by

$$L = \frac{R}{\omega}\tan 49.052^\circ$$

$$C = \frac{1}{\omega R}\frac{8}{\pi(\pi^2 + 4)} = \frac{1}{5.4466\omega R}$$

$$R = \frac{8}{\pi^2 + 4}\frac{V_{cc}^2}{P_{out}} = 0.5768\frac{V_{cc}^2}{P_{out}}$$

$$C_0 = \frac{1}{\omega R Q_L} \qquad L_0 = \frac{1}{\omega^2 C_0}$$

The above given analytical results for idealized Class E operation conditions do not take into account the possible losses caused by non-ideal active device properties, for example, due to the finite value of the saturation resistance r_{sat} and switching time between "on" and "off" operation conditions. The second effect can be explained by the device inertia when the base charge changes to zero with some time delay τ_a. As a result, the base charge process, but not the appropriate load network, determines the collector current waveform during this active stage due to the time delay. So, for a 50-percent duty cycle, the averaged dissipated power P_{sat} can be evaluated by [4]

$$P_{sat} \cong \frac{8}{3}\frac{r_{sat}P_{out}^2}{V_{cc}^2}$$

whereas the losses at the active stage due to the finite time between "on" and "off" operation conditions described by the active phase loss power P_a can be approximately calculated by [5]

$$P_a \cong \frac{\tau_a^2}{12} \qquad \text{for } \Delta\tau = 100 \div 260^\circ$$

The losses at the active phase are sufficiently small and, for example, for $\tau_a = 0.35$ or 20° are only 1%.

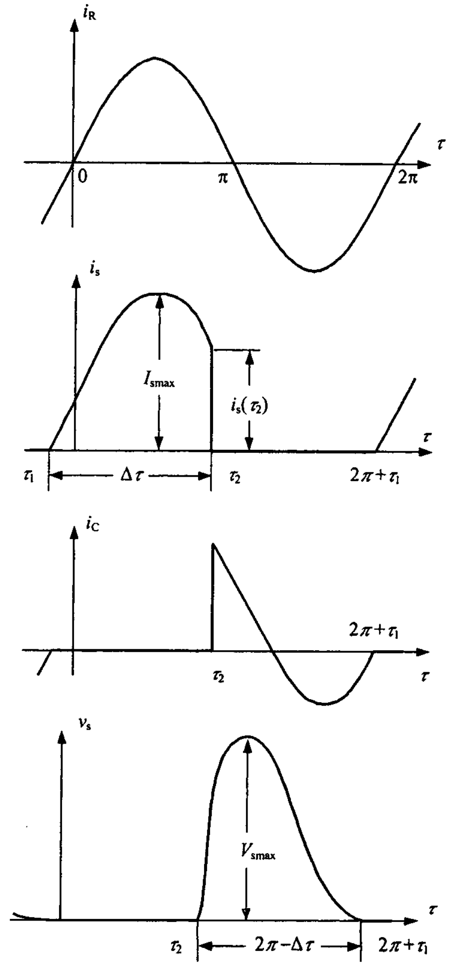

Fig. 3. Voltage and current waveforms for optimum Class E operation with shunt capacitance

III. CLASS E WITH PARALLEL CIRCUIT

In Figure 4, the switched-mode tuned Class E power amplifier with parallel circuit is shown. According to a generalized approach given in [5], the voltage and current waveforms can be represented as shown in Figure 5. The detailed calculation of the optimum parameters for 50% duty cycle is given in [8].

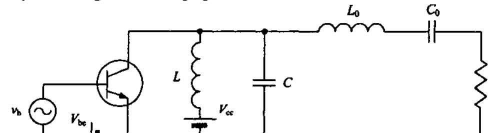

Fig. 4. Class E power amplifier with parallel circuit

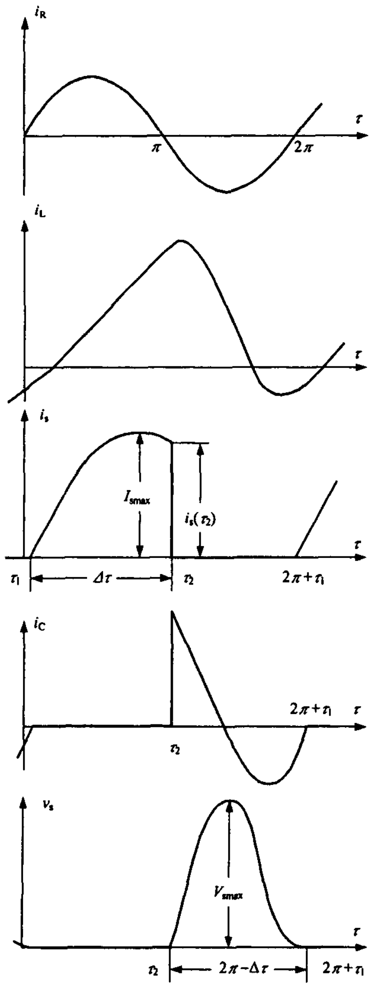

Fig. 5. Voltage and current waveforms for optimum switched-mode power amplifier with parallel circuit

IV. CLASS E WITH SHUNT INDUCTANCE

Another approach to the design of the Class E power amplifier with efficiency of 100% under idealized operation conditions is to use the circuit configuration with shunt inductance [9]. This amplifier is similar to the Class E power amplifier with shunt capacitance but with a shunt inductance as the storage element instead of a shunt capacitance. The basic circuit of the Class E power amplifier with shunt inductance is shown in Figure 6.

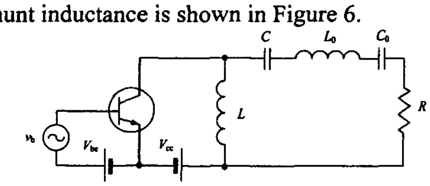

Fig. 6. Switched-mode power amplifier with shunt inductance

In the class E power amplifier with shunt inductance, it is possible to eliminate the power losses providing the on-to-off state device operation with the following current conditions:

$$i_s(\omega t)\big|_{\omega t=2\pi} = 0, \qquad \left.\frac{di_s(\omega t)}{d(\omega t)}\right|_{\omega t=2\pi} = 0$$

when the transistor switches off at $\omega t = 2\pi$.. The load network parameters can be calculated from

$$\frac{\omega L}{R} = \frac{\pi(\pi^2+4)}{8} = 5.4466$$

$$\omega CR = \frac{16}{\pi(\pi^2+12)} = 0.2329$$

$$R = \frac{V_{cc}^2}{P_{out}}\frac{8}{\pi^2(\pi^2+4)} = 0.05844\frac{V_{cc}^2}{P_{out}}$$

$$C_0 = \frac{1}{\omega R Q_L} \qquad L_0 = (Q_L - 4.2941)\frac{R}{\omega}$$

From idealized voltage and current waveforms shown in Figure 7 it follows that, when the switch is open, the current through the device i_c is zero and the current i_R is determined by the sinusoidal current i_L. However, when the switch is closed, the voltage v_c is zero and supply voltage V_{cc} produces the linearly increasing current i_L. The difference between the current i_L and current i_R flows through the switch.

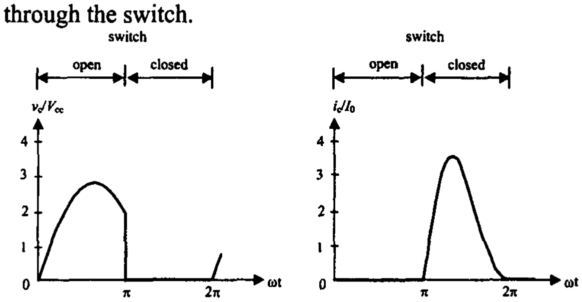

Fig. 7. Collector voltage and current waveforms for optimum Class E power amplifier with shunt inductance

The previous analysis was based on the assumption of zero device output capacitance. But at high frequencies this capacitance cannot be considered as negligible and should be taken into account. In this case, the power amplifier operates in switching mode with parallel circuit and series capacitance but the required idealized operations conditions must be realized with zero-current switching. However, the theoretical analysis given by [10] illustrates the infeasibility of a zero-current switched-mode Class E power amplifier to approach 100-percent collector efficiency with non-zero device output capacitance. This means that the harmonic impedance conditions should be different, being inductive for fundamental and capacitive for higher-order harmonics or capacitive for fundamental and inductive for higher-order harmonics, which can be achieved only with zero-voltage switching conditions.

V. CLASS E WITH TRANSMISSION LINES

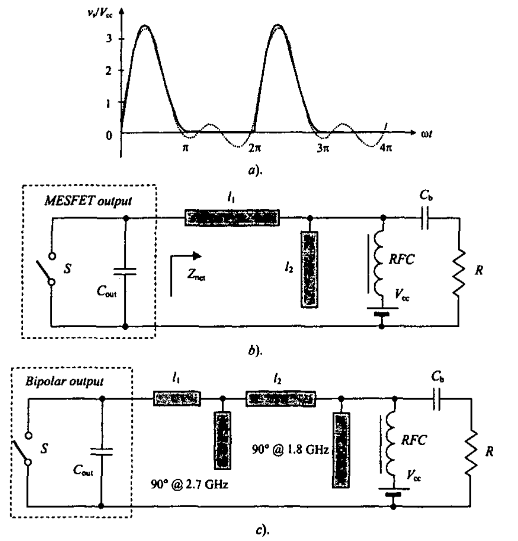

Fig. 8. Two-harmonic voltage waveform and equivalent circuits of Class E power amplifiers with transmission lines

For microwave power amplifier, usually all inductances in its output matching circuit should be realized by means of the transmission lines in order to reduce power losses. As a result, to approximate the idealized Class E operation conditions, it is necessary to design the transmission-line load network satisfying the required idealized optimum impedance at fundamental given by

$$Z_{\text{net1}} = R\left(1 + j\tan 49.052^\circ\right)$$

At the same time, the open-circuited conditions should be realized at all of the higher-order harmonics. However, as it turned out from the Fourier analysis, a good approximation to Class E mode may be obtained with only two harmonics (fundamental and second) of the voltage waveform across the switch [11]. In Figure 8(*a*), the voltage waveform containing these two harmonic (dotted line) are plotted along with the ideal one (solid line). Applying this approach the Class E power amplifier with series microstrip line l_1 and open-circuited stub l_2, which equivalent circuit is shown in Figure 8(*b*), was designed for microwave applications. The electrical lengths of lines l_1 and l_2 are chosen to be of about 45° at the fundamental giving an open circuit condition at the second harmonic, whereas their characteristic impedances are calculated to satisfy the required inductive impedance condition at the fundamental. The output lead inductance of the packaged device can be accounted for by a shortening the length of l_1.

An additional increase of the collector efficiency can be provided by the load impedance control at the second and the third harmonics [12]. Such a harmonic control network consists of the open-circuited quarter-wave stubs both at the second harmonic and third one separately, as shown in Figure 8(*c*), where the third-harmonic quarter-wave stub is located before the second-harmonic one. And it is possible to achieve very high collector efficiency even with values of the device output capacitance higher than conventionally required at the expense of lower output power keeping the load at the second and third harmonics strictly inductive. As a result, maximum collector efficiency over 90% for power amplifier with the output power of 1.5 W can be realized at 900 MHz.

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