Amplitude Modulation of the Class E Power Amplifier

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Abstract **In this paper is presented a highly effective radio-frequency power amplifier class E. The linear dependence of the amplitude output voltage from the supply voltage gives opportunity for its usage at the radio transmitters of AM signals. Here are presented the analytical dependences of the amplifier's parameters when working in carrier modes and AM signals. The amplitude frequency, static modulation, dynamic modulation and frequency modulation characteristics of the amplifier with output peak power P_{pk}=116 W and working frequency f_s = 3.5 MHz are presented.**

Keywords – **Amplitude Modulation, High Efficiency RF Power Amplifier, Class E .**

I. Introduction

RF power amplifiers, class E occur determining for the energetic, and technical-economical parameters of the radio transmitters. The best way for increasing the efficiency of the power amplifier is the usage of the switch working mode, due to which under certain conditions is achieved a maximum efficiency and the output power in the load.

The resonant amplifiers class E, working in the switch mode absolutely satisfy these requirements as they work at efficiency above 96%.

It has got a linear dependence of the output voltage from the voltage of the drain, as the angle of conduction and the form of the output voltage do not depend on the change of the supply voltage. This leads to linear modulation characteristics, as the distortion of the modulation envelope can easily be done under 1%.

II. Theoretical analisis

A. Carrier mode

The basic circuit of power amplifiers class E working in carrier mode is shown on fig. 1. MOSFET transistor is used which turns periodically with the carrier frequency. The optimal effective work of the amplifiers class E is obtained when the voltage on the transistor V_{DS} and its declination (dV_{DS}/dt) are zero [1], [2], [5], [7], when transistor turns on. The maximum power is obtained when duty cycle is 50 % [1], [6].

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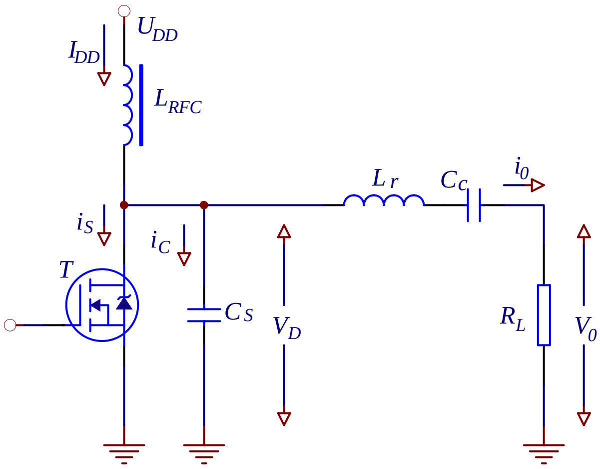

Fig. 1. A basic circuit of power amplifiers class E

For analysis and design of amplifier in optimal mode is done the equivalent circuit on fig. 2. For duty cycle 50 % should be satisfied the following ratios: [1], [2], [6]. For analysis L_r is divided to L_c and ΔL. ΔL is obtained from the equation

$$\Delta L = \frac{\pi(\pi^2 - 4)R_L}{16\omega_c} \approx 1.1525\frac{R_L}{\omega_c} \quad (1)$$

The following equations are used to obtain:
- the inductance

$$L_c = \frac{(Q - 1.152)R_L}{\omega_c} \quad (2)$$

- the capacitances

$$C_c = \frac{1}{L\omega_c^2} \quad (3)$$

and

$$C_s = \frac{8}{\pi(\pi^2 + 4)\omega_0 R_L} \approx \frac{0.1836}{\omega_c R_L} \quad (4)$$

- the resonant frequencies

$$\omega_r = \frac{1}{\sqrt{C_c L_r}} = \frac{1}{\sqrt{C_c(L_c + \Delta L)}} \quad (5)$$

and the quality factor

$$Q_r = \frac{\omega_r L_r}{R_L} = \frac{1}{\omega_r C R_L} \quad (6)$$

Resultant resonant circuit has lower resonant frequency ω_r from the frequency of the carrier ω_c, which is determined by the value of the qualitative Q_r. This leads to non-linear distortions of AM output voltage on R_L, because the upper and lower side bands of the modulated oscillation are transmitted through the load resonant circuit with different amplitude and delay. This occurs especially at the amplification of SSB signals.

In order to eliminate the influence of the inductance L_{RFC} on the distortion AM signal should satisfy the condition [4]

$$L_{RFC\min} = \left(\frac{\pi^2}{4}+1\right)\frac{R_L}{f_c} \approx 3.5\frac{R_L}{f_c} \qquad (7)$$

B. AM at amplifier class E

On the compiled equivalent scheme for the aims of the analysis the switching transistor is modeled as a switch in series with a static drain-to-source on-resistance (Fig. 2). The amplitude of the output voltage is proportional to the voltage on the drain V_D [1], [2], [4]

$$V_{0m} = \frac{4}{\sqrt{\pi^2+4}}\left(V_{DD}-V_{R_{ON}}\right) \approx 1.074\left(V_{DD}-V_{R_{ON}}\right) \qquad (8)$$

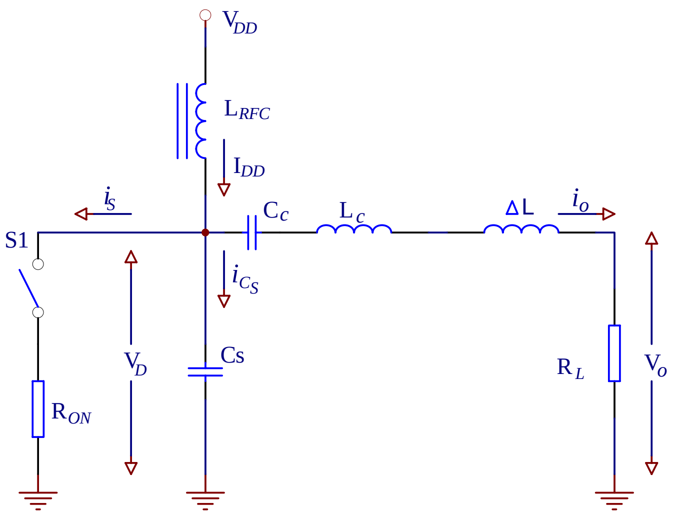

Fig. 2. Equivalent circuit of amplifier class E

Amplitude modulation with a good linearity could be obtained when the voltage on turn-on transistor depends on the current through the drain; the controlling signal at high frequencies passing through the capacitance C_{GD} does not exert influence when the modulating signal is of a little value and the output capacity of the transistor C_{DS} is not with significant value in respect of C_S .

The analysis of the amplitude modulation at amplifier class E is done on the basis of the equivalent circuit shown on Fig. 2 under the following assumptions:

-the static modulation characteristic $V_{0m}=f(V_{DD})$ is linear and is described by the expression (8);

-the distortions caused by the inductance L_{RFC} are zero, condition (8);

-the amplifier works in optimal, condition from (1) to (4).

At the analysis will be used harmonious modulating oscillation

$$v_m(t) = V_m \cos\omega_m t \qquad (9)$$

From AM signal obtained at the output of the amplifier only the fundamental component transmits to the load (carrier, lower and upper side bands) while other components are suppressed by resonant circuit.

$$v_{D1}(t) = V_{D1}(1+m\cos\omega_m t)\cos\omega_c t =$$
$$= V_{D1}\left[\cos\omega_c t + \frac{m}{2}\cos(\omega_c-\omega_m)t + \frac{m}{2}\cos(\omega_c+\omega_m)t\right] \qquad (10)$$

The voltage transfer function from the drain to R_L is

$$\overline{K} = Ke^{j\varphi} = \frac{1}{1+j\left(\frac{\omega L_r}{R_L}-\frac{1}{\omega C_c R_L}\right)} = \frac{1}{1+jQ_r\left(\frac{\omega}{\omega_r}-\frac{\omega_r}{\omega}\right)} =$$
$$= \frac{1}{1+jQ_r\left(\frac{\omega_c}{\omega_r}\cdot\frac{\omega}{\omega_c}-\frac{\omega_r}{\omega_c}\cdot\frac{\omega_c}{\omega}\right)} \qquad (11)$$

where Q_r is determined by expression (4). From (1) and (4) we can write down

$$\frac{\omega_c}{\omega_r} = \frac{\frac{\pi(\pi^2-4)}{16}+\sqrt{4Q_r^2+\left[\frac{\pi(\pi^2-4)}{16}\right]^2}}{2Q_r} \qquad (12)$$

From (10), we obtain modules and arguments of voltage of the transfer function at the carrier frequency ω_c, lower sideband (ω_c - ω_m) and upper sideband (ω_c + ω_m).

$$K_c = K(\omega_c) = \frac{1}{\sqrt{1+\left[\frac{\pi}{16}(\pi^2-4)\right]^2}} \approx 0.665 \qquad (13)$$

$$\varphi_c = \varphi(\omega_c) = -\arctan\left[\frac{\pi}{16}(\pi^2-4)\right] \approx 49.05^0 \qquad (14)$$

$$K_l = K(\omega_c-\omega_m) =$$
$$= \frac{1}{\sqrt{1+\left\{Q_r\left[\frac{\omega_c}{\omega_r}\left(1-\frac{\omega_m}{\omega_c}\right)-\frac{1}{\frac{\omega_c}{\omega_r}\left(1-\frac{\omega_m}{\omega_c}\right)}\right]\right\}^2}} \qquad (15)$$

$$\varphi_l = \varphi(\omega_c-\omega_m) =$$
$$= -\arctan\left\{Q_r\left[\frac{\omega_c}{\omega_r}\left(1-\frac{\omega_m}{\omega_c}\right)-\frac{1}{\frac{\omega_c}{\omega_r}\left(1-\frac{\omega_m}{\omega_c}\right)}\right]\right\} \qquad (16)$$

$$K_u = K(\omega_c + \omega_m) = = \frac{1}{\sqrt{1+\left\{Q_r\left[\frac{\omega_c}{\omega_r}\left(1+\frac{\omega_m}{\omega_c}\right)+\frac{1}{\frac{\omega_c}{\omega_r}\left(1+\frac{\omega_m}{\omega_c}\right)}\right]\right\}^2}} \tag{17}$$

$$\varphi_u = \varphi(\omega_c + \omega_m) = = -\arctan\left\{Q_r\left[\frac{\omega_c}{\omega_r}\left(1+\frac{\omega_m}{\omega_c}\right)-\frac{1}{\frac{\omega_c}{\omega_r}\left(1+\frac{\omega_m}{\omega_c}\right)}\right]\right\} \tag{18}$$

From expressions (10) and (13) to (18) we fix AM output tension

$$v_0(t) = V_{D1}\{K_c\cos(\omega_c t + \varphi_c) + +\frac{m}{2}K_l\cos[(\omega_c - \omega_m)t + \varphi_l] + +\frac{m}{2}K_u\cos[(\omega_c + \omega_m)t + \varphi_u]\} \tag{19}$$

The output voltage could be written as

$$v_0(t) = V_0(t)\cos[\omega_c t + \phi(t)] \tag{20}$$

The amplitude V_0 *(t)* and the initial $\phi(t)$ of the output voltage change due the course of time. Essential is the change of the amplitude

$$V_0(t) = V_{D1}\left\{\left[K_c\cos\varphi_c + \frac{m}{2}K_l\cos(\omega_m t - \varphi_l) + +\frac{m}{2}K_u\cos(\omega_m t + \varphi_u)\right]^2 + +\left[K_c\cos\varphi_c - \frac{m}{2}K_l\sin(\omega_m t - \varphi_l) + +\frac{m}{2}K_u\sin(\omega_m t + \varphi_u)\right]^2\right\}^{1/2} \tag{21}$$

As a result of this that the amplifier works at higher frequency than resonant for C_c $-L_r$ resonant circuit upper sideband is transmitted suppressed with less amplitude and larger phase. The two sidebands components are transmitted from the drain to R_L with different magnitudes and different delays. This causes harmonic distortion of the envelope of the AM output voltage [4]. In addition, the fundamental component of the envelope decreases with f_m .

III. Results

On the basis of above formulated material was designed power amplifier class E with the following parameters $f_c=3.5$ *MHz*, $L_{RFCmin}=50$ *μH*, *Lc =20.12 μH*, *Cc=100 pF*, *ΔL=2.62 μH*, $C_s=167$ *pF*, $R_L=50$ *Ω* ,*Q=10*, $V_{dc}=50$ *V*, $V_m=50$ *V*, $P_{pk}=115$ *W*, $P_{out}=25$ *W* and MOSFET transistor IRFBC40.

A computer simulation is executed on the power amplifier. We examined its work in carrier mode. On Fig. 3 are shown the waveforms of the control voltage, the voltage at the output of the amplifier, the waveform of the current through radio frequency choke, the waveform voltage on the load. Results show the work of the amplifier at optimal mode.

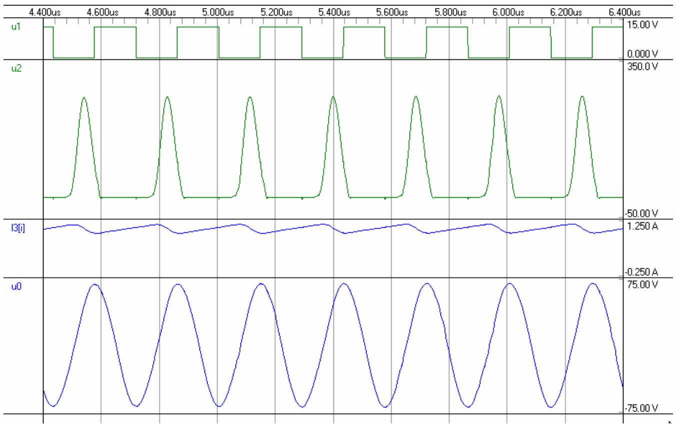

Fig. 3. Waveform of the voltages at amplifier class E

Here is shown the static modulation characteristic of the amplifier which presents the dependence of the output voltage from drain voltage $V_{0m}=f(V_D)$. The dependence is comparatively linear and it is a precondition for a linear amplitude modulation.

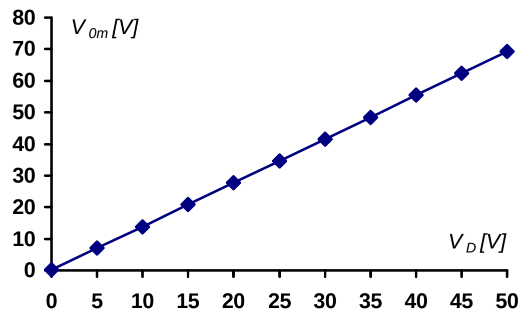

Fig. 4. Dependence $V_{0m}=f(V_D)$.

In RF range the modulating signals AM are with frequency band not wider than 4,5 kHz. That is why measured frequency modulation characteristic $m=f(f_m)$ is done in such frequency range. Modulation index *m* changes with not more than 1,2 % in the whole frequency range which for office connections and broadcasting completely satisfy the requirements.

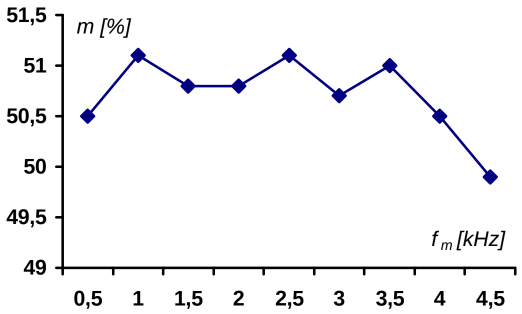

Fig. 5. Dependence $m=f(f_m)$

The dependence of modulation index from modulation voltage $m=f(V_m)$ is the dynamic modulation characteristic shown on Fig.6. The characteristic is linear, which is a factor for reduction of the distortion of the form of envelope at AM.

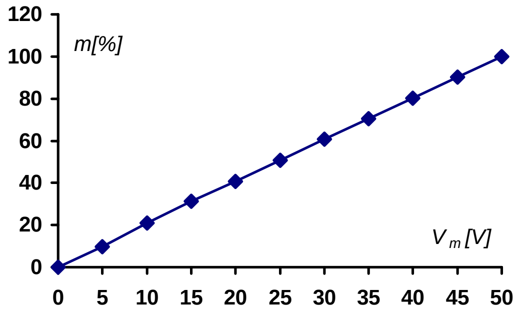

Fig. 6. Dependence $m=f(V_m)$

The work of power amplifier class E in a mode of amplitude modulation with $m=100$ % is shown on Fig. 7. The waveform of the voltage on the drain V_D and on the load V_0 shows that there are not distortions.

Results show that amplifier can be used successfully for constructing of radio transmitters for AM and CW.

IV. Conclusion

The precise analysis of resonant amplifier class E shows that it works very well with AM signals. The non-linear distortions of envelope of AM output are a result of the following reasons: transistor; output load circuit; radio frequency choke.

The non-linear distortions caused by transistor are very low in view of the fact that the conduction angle and the form of the output voltage are not change by variations of the supply voltage. The serial resonant circuit in the load circuit should be detuned by the carrier frequency to obtain optimum-efficiency operation of the amplifier. The distortions increases with the relation of modulation and carrier frequency f_m/f_c, the depth of the modulation m and the qualitative factor of the load circuit Q_r and they can reach mote than 10 %.

The non-linear distortions could be reduced under 1 % if $f_c/f_m > 50$ and $Q_r > 15$. Radio frequency choke should be chosen by compromise between the distortions and the optimal work of the amplifier. Too high inductance of the radio frequency choke reduces the depth of modulation m, while too low one disturbs the effective performance. The simulation shows that the process of amplitude modulation in amplifier class E is very good.

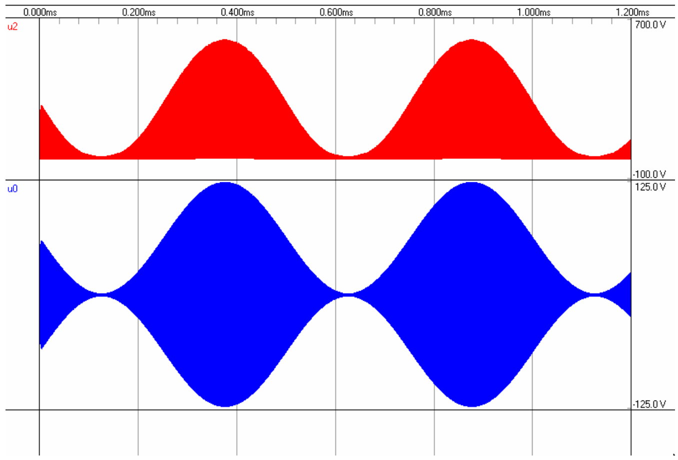

Fig. 7.The waveform of V_D and V_0.

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