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Amplitude Modulator in Class E with the Current Mirror in Emitter Circuits of the Switching Transistor

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Abstract: Starting from the fact that the amplitude of the basic harmonics of the current, flowing through load resistor of the class E power amplifier, is proportional to direct current flowing through the collector battery of the switching transistor, an introduction of a current mirror in emitter circuit of the transistor in whose reference branch is situated a generator of modulating voltage is proposed. It can be easily proven that the total current of this mirror, which is also the direct current of the collector battery, has the waveform of of the amplitude modulated signal. This amplidude modulator is verified for performance with pSpace model.

Keywords: Power amplifier, class E operation, efficiency, amplitude modulator, current mirror.

1 Introduction

IN APPLIANCES where high efficiency and output power have important roles, selective power amplifiers are used. In fact, these electronic circuits transform power of the supplying source into high-frequency power. The primary issue of each power transformation is the degree of efficiency. Thus, apart from linearity of the amplifier's transformation characteristic, it plays a role of fundamental importance. The class E power amplifiers are realized by one transistor functioning as a switch and a series oscillator circuit. This concept was introduced for the first time by Nathan Sokal and Aalan Sokal (father and son) in 1975. This class of amplifiers is characterized by very high efficiency, in the ideal case, it is 100%, but in practical applications it is up to 96%.

N. Sokal and A. Sokal in [1], and Kazimierczuk in [2], provided detailed analysis of the class E power amplifiers, while in [3] a solution for the realization of

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amplitude modulation modulators has been proposed. The base of the proposed solution is Darlington's amplifier, which is situated between collector battery and collector of the switching transistor, which is induced by modulating voltage. Altough, it was shown in [2, 4, 5, 6], thatthe amplitude of the basic harmonic of current flowing through load resistor is proportional to direct current flowing through the battery for supplying collector circuit V_{CC}, that fact has not been used for analysis of amplitude modulators.

This paper is proposes the introduction of the current mirror in emitter circuit of the switching transistor instead of Darlington's amplifier. A generator of modulating voltage is situated in the branch through which the reference current is flowing, therefore, as it is known, that current is equal to the collector current of the mirror. This current, beside the direct component contains the current proportional to the modulating voltage, hence the amplitude of the current of the frequency corresponding to the first harmonic of the impelling signal has the shape of amplitude modulated signals.

2 The Class E Power Amplifier

In Figure 1, a class E power amplifiers is shown induced by a sequence of square impulses, where positive half-period of the impulse leads transistor into saturation, and negative one into cutoff mode. The transistor practically operates as a switch with two states [3, 7, 8, 9]. Amplifier's collector circuit contains a parallel capacitance C, a series tuned oscillator circuit $C_0 - L$, and load resistor R. It is supplied through the choke inductance. Elements C_0 and L_0 build the series oscillator circuit, which is tuned to the frequency of operating voltage, while inductance L_r remains form the coil, since optimal operating mode is performed out of the resonance.

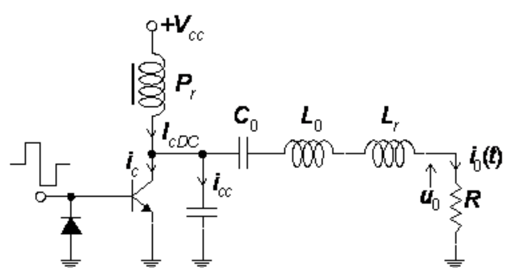

Fig. 1. Class E power amplifier.

The quality factor Q of the oscillator circuit, if losses in the coil are neglected, is given by:

$$Q = \frac{\omega_0 L}{R} = \frac{\omega_0 (L_0 + L_r)}{R} \tag{1}$$

where $\omega_o = 1/\sqrt{L_0 C_0}$. The value of the Q-factor should be much higher then one, since the higher harmonics of current flowing through load resistor should be attenuated and neglected. On the other hand, the value of the Q-factor also should not be too high, since own losses in the coil L, would become larger, which would subsequently decrease the degree of efficiency.

This means that the selection of the factor has to be a compromise, which needs to be resolved within given working circumstances of the amplifier. In order to eliminate loss of the power on the collector caused by switching from the cutoff to the saturation mode it must be:

$$\begin{aligned} &u_{CE}(2\pi) = 0 \\ &\left.\frac{\mathrm{d}u_{CE}}{\mathrm{d}t}\right|_{\omega t = 0} = 0 \end{aligned} \tag{2}$$

where transistor for $\omega t = 2\pi$ switches to the saturation mode.

An equivalent amplifier's scheme for both modes of the switching transistor is given in the Figure 2. It consists of a switch S, a bias choke P_r, a capacitance C, a tuned circuit $L - C_0$, and a load resistor R. The transistor switch S is ON half of the period, and OFF in the other half. When switch S is ON, the voltage across switch S is zero, and when it is off, the current through switch S is zero. The capacitance C includes the parasitic capacitance across the transistor. The $L - C_0$ circuit resonates at the fundamental frequency of the input signal and only passes a sinusoidal current to the load resistor R.

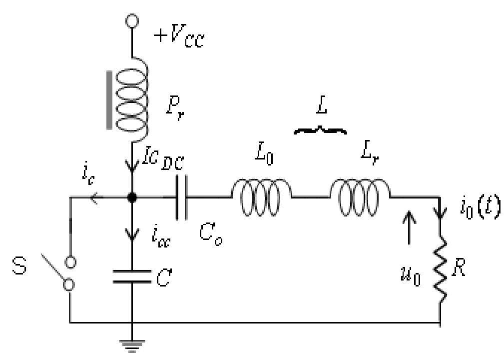

Fig. 2. Class E power amplifier-equivalent circuit.

Based on Figure 1 it can be written:

$$I_{cDC} - i_0 = i_c + i_{cc} \tag{3}$$

where I_{cDC} is the direct current flowing through the battery V_{cc}, i_0 is current of the fundamental harmonics flowing through load resistor, i_c is the collector current of transistor, and i_{cc} is the current flowing through capacitor C.

The current flowing through load resistor is sinusoidal due to presence of series oscillator circuit, and the assumption that its quality factor Q is large enough:

$$i_0 = J_{0m} \sin(\omega t + \varphi) \tag{4}$$

where J_{0m} and φ are amplitude and phase of the first harmonics, respectively.

Based on the analysis of equivalent, Figure 2, circuit like in [1] and [4], it could be found that the fundamental harmonic of the current through load resistor is given by:

$$J_{0m} = \frac{I_{cDC}}{\sin\varphi} \tag{5}$$

where $\sin\varphi = 2/(\sqrt{\pi^2+4})$ and φ is the phase of the current, generated by inductance L in the circuit between load resistor and the collector. If the components which refer to the direct current and modulating signal are added, the amplitude modulation can be performed.

Marian Kazimierczuk [2] has based his analysis of the class E amplifiers on the large choke inductance, therefore the direct current component flowing through the choke inductance only, and since the amplifier is designed for the given high frequency power - P_{out} the network elements are

$$\begin{aligned} R &= \frac{8}{\pi^2+4}\frac{V_{CC}^2}{P_{out}} \qquad & C &= \frac{1}{\omega_0 R}\frac{8}{\pi^2+4} \\ L_r &= \frac{R}{\omega_0}\frac{\pi^2+5}{16} \qquad & L &= \frac{QR}{\omega_0} \end{aligned} \tag{6}$$

3 A New AM Modulator

The scheme of the new amplitude modulator with current mirror is given in Figure 3. Because T_1 and T_2 are matched, their β_0-values also agree, making the mirror output current the same as the collector current of T_2. Parameter β_0 is the transistor β-value for $V_{CB} = 0$ V.

In the proposed circuit in the reference branch of current mirror is connected the source of modulating voltage $u_n(t)$. It can be easily shown that reference current of the current mirror is

$$i_r = \frac{V_{EE} - V_{BE} + u_n(t)}{R_r} = \frac{V_{EE} - V_{BE}}{R_r} + \frac{u_n(t)}{R_r} \\ = I_{r0} + \frac{u_n(t)}{R_r} \tag{7}$$

where V_{BE} is voltage between base and emitter of the transistor T_3 and V_{EE} is voltage source.

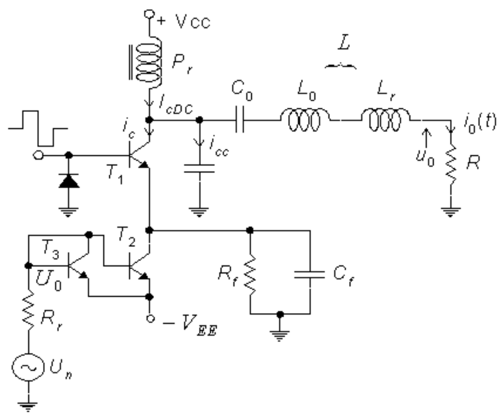

Fig. 3. Amplitude modulator with the current mirror.

When $L_0 - C_0$ circuit is in resonance, only the fundamental harmonic of the current i_0 causes voltage drop on the load resistor R_p, therefore the output voltage is

$$u_0(t) = I_{0m} R_p \cos(\omega_v t) \tag{8}$$

and $\omega_v = 1/T_v$ is frequency of the input impulses, and $U_n f(t)$ is modulating voltage, where U_n is amplitude and $f(t)$ waveform of the modulating voltage.

The current given by equation (8) is direct current, it is the direct current of the current mirror that is equal to the direct current through battery V_{CC}.

$$u_0(t) = R_p I_{r0}[1 + m\cos(\omega_n t)]\cos(\omega_v t) \tag{9}$$

where $I_{cDC} = I_{r0}$ and $m = U_n/(V_{EE} - V_{BE})$ is degree of modulation. The voltage amplitude on the load resistor R is $U_{0m} = RI_{0m}$, and for optimal values of the elements, for 100% degree of efficiency, it is $V_{CC} + V_{EE}$. In order to prevent consumption of the high frequency power in the current mirror that part of the circuit is spanned by a $R_f C_f$ filter, like it is done in [3] with Darlington's amplifier.

In order to verify performance in time-domain the simulation is performed on pSpace model. The parameters of modulator is $C_0 = 1.67892$ nF, $L_0 = 7,602\mu$H, $L_{rf} = 8592.55\mu$H, $C = 5.5$nF, driving signal frequancy $f = 1$ MH, and Q-factor of the series resonat circuit is 5.

4 Conclusion

In this paper a new amplitude modulator is proposed. It is based on the modification of the class E amplifiers, in a way that a current mirror in whose reference branch is positioned source of the modulating voltage in emitter circuit of the switching transistor is added. It is shown that output voltage has waveform of ampltude modulated signals. It can be noticed that the new modulator is similar to the linear one, with a difference that inducement, on the place where the modulation carrier is situated in linear amplifiers, consists of a sequence of square impulses, and selective output impedance is a circuit, typical for class E.

In order to verify performance in time-domain the simulation is performed on pSpace model.

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