Class E Amplifier in Push-Pull Configuration

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Abstract: This paper proposes, for the first time, the design of class E pull-push power amplifier. With the new design, the output power is increased by four times when compared to conventional single-end class E connection amplifier with the same supply voltage. The performance of the proposed amplifier is verified by with a 100-kHz power amplifier constructed using general-purpose NPN transistors.

1. Introduction

In 1975, Sokal and Sokal [1] introduced the Class E amplifier with a 100% theoretical collector efficiency. Li and Yam then derived an analytical method [5], [6] for analysing this kind of amplifiers in 1994. Based on these works, we introduce a new configuration called class E push-pull amplifier to further enhance the power efficiency by four times. Both theoretical analysis and experimental results of the design will be presented in this paper.

2. Theory

Figure 1 shows the proposed class E push-pull amplifier. The transistors T^+ and T^- in the amplifier work alternatively. When a negative cycle of an input signal is fed into the primary coil, transistors T^+ will be turned on; namely, each transistor of the amplifier works for either positive or negative cycle of the input signal. The peak-to-peak voltage is shared by the transistor T^+ and T^- instead of the whole voltage range for a single transistor in conventional single-ended class E amplifier. In addition, the push-pull amplifier doubles the voltage delivering to the load resistor (R_L) and the output power of the amplifier can be increased by four times.

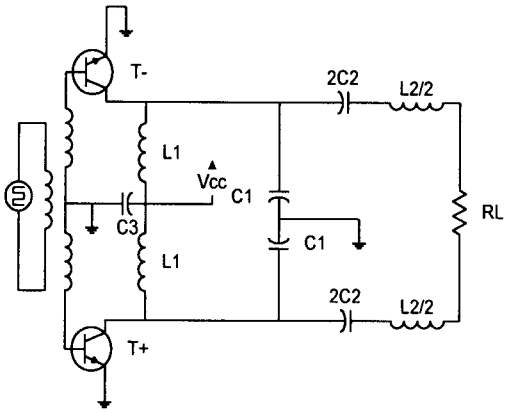
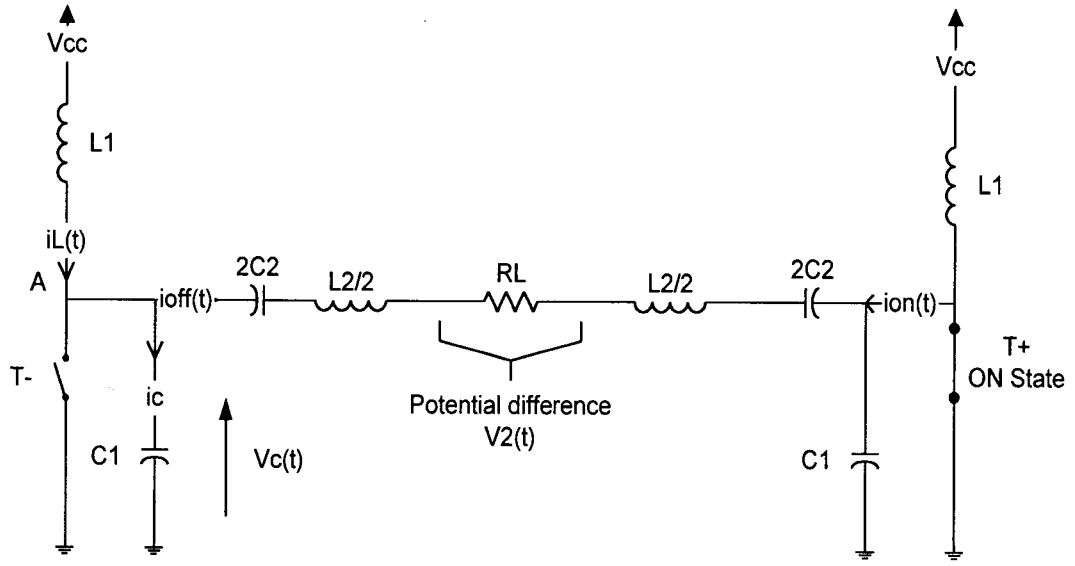
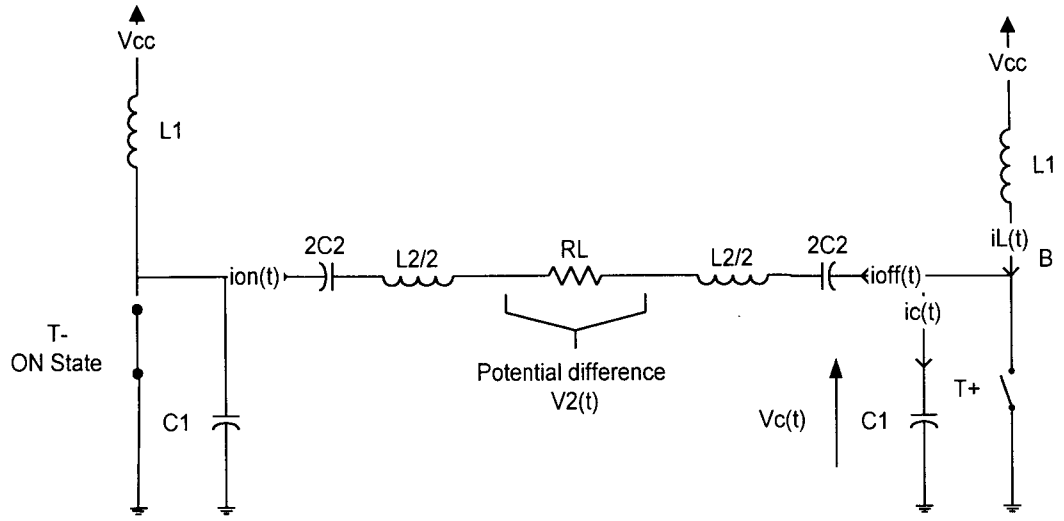


Figure 1. Circuit diagram of the proposed class E push-pull Amplifier.

Using the approach developed for single-end class E amplifier [5], an equivalent circuits for Figure 1 is derived and the result is shown in Figure 2.



(a)



(b)

Figure 2. The equivalent circuit of the amplifier: (a) negative cycle; (b) positive cycle.

For sake of simplicity, the following assumptions are made:

i. The amplifier is driven by a signal with period T, angular frequency ω and 50% duty cycle.
ii. The output signal is periodic and sinusoidal.
iii. Congruent transistor T & T^+ with zero ON state and infinity OFF state resistance are used.
iv. Components have no loss.

Applying KCL at point A during negative input state, we get

$$i_{off}(t) - i_{on}(t) = i_L(t) - i_c(t) \qquad (1)$$

For positive cycle, the current has the same magnitude but with opposite direction. Thus, the current flowing through R_L will be

$$\begin{cases} i_L(t) - i_c(t) & 0\langle t\langle \pi \\ -\left[i_L(t) - i_c(t)\right] & \pi\langle t\langle 2\pi \end{cases} \qquad (2)$$

or

$$\begin{cases} i_L(t) - i_c(t) & 0\langle t\langle \pi \\ -\left[i_L(t+\pi) - i_c(t+\pi)\right] & 0\langle t\langle \pi \end{cases}$$

And the total current through the load R_L is equal to

$$i_L(t) - i_c(t) - \left[i_L(t+\pi) - i_c(t+\pi)\right] \qquad (3)$$

If all AC signals are composed of sinusoidal only, a 180° phase lag represents an inversion of the signal and equation (3) becomes

$$2 \times \left[i_L(t) - i_c(t)\right] \qquad (4)$$

Assuming the output current is sinusoidal, the output current will be $2 \times I_0 \sin(\omega t + \phi)$ and we have

$$i_L(t) - i_c(t) = I_0 \sin(\omega t + \phi) \qquad (5)$$

where I_o is the amplitude of output current, ϕ is the phase difference between the input and output signals and ω is the angular frequency of input signal.

Considering KCL at point A or B, we have

$$Vcc = L_1 \frac{di_L}{dt} + V_c \qquad (6)$$

$$C_1 L_1 \frac{d^2 i_L}{dt^2} + i_L = I_0 \sin(\omega t + \phi) \qquad (7)$$

In the positive input cycle, T is in 'on' state. The equivalent circuit of the amplifier is shown in Figure 2b. Where C_1 will be virtual grounded and the device T^+ is 'off'. In the period $\frac{\pi}{\omega} \le t < \frac{2\pi}{\omega}$, we have

$$i_L(t) = \frac{Vcc}{L1}(t - \frac{\pi}{\omega}) + C \qquad (8)$$

where C is a constant depending on $i_L(\frac{\pi}{\omega})$

As described in the analytic method [6], the boundary conditions of the amplifier can be obtained by considering:

i. the continuity of $I_L(t)$ for the transition between ON and OFF states;
ii. the continuity of $V_c(t)$ for the transition between ON and OFF state; and
iii. the 100% power efficiency operating conditions, i.e.

$$V_{c1}(t) = 0\Big|_{t=\frac{\pi}{\omega}} \text{ and } \frac{dV_{c1}(t)}{dt} = 0\Big|_{t=\frac{\pi}{\omega}} \quad (9)$$

With these constraints, it can be readily shown that the output power is given

$$P_{out} = -\frac{2V_{CC}}{\pi}\left[\frac{A}{\omega_0}\left(\pi\cos\frac{\pi}{\beta} + \beta\sin\frac{\pi}{\beta}\right) - \right.$$
$$-\frac{B}{\omega_0}\left(\beta\cos\frac{\pi}{\beta} - \beta - \pi\sin\frac{\pi}{\beta}\right) + \quad (10)$$
$$\left. + \frac{2I_0\cos\phi - \pi I_0\sin\phi}{(\beta-1)(\beta+1)}\right]$$

where $\omega_o = \frac{1}{\sqrt{L_1 C_1}}$, $\beta = \frac{\omega}{\omega_o}$,

$$B = \left(\frac{V_{CC}}{L_1} - \frac{I_0\omega\cos\phi}{1-\beta^2}\right)/\omega_0,$$

$$A = \frac{1}{1-\cos\frac{\pi}{\beta}}\left(\frac{V_{CC}}{L_1\omega_0}\sin\frac{\pi}{\beta} - \sin\frac{\pi}{\beta}\frac{I_0\beta\cos\phi}{1-\beta^2} - \right.$$
$$\left. - \frac{2I_0\sin\phi}{1-\beta^2} + \frac{\pi V_{CC}}{\omega L_1}\right)$$

And the load resistance is $R_L = \frac{2p_{out}}{(2I_o)^2}$

From the above modelling, the characteristic equations of the push-pull amplifier are found to be essentially the same as that of the single-end ones [6]. Hence component values similar to the previous design can be used with minor modifications: the series components between the two transistors should be split into two in parallel or in series.

3. Experimental Results

To verify the proposed design, a 100-kHz push-pull Class E was constructed using two general-purpose NPN transistors. The experimental waveforms of the collector voltage and current are depicted in Figure 3a which shows that the amplifier array is in optimal condition and has no overlapping region between switching voltage and current. The negative voltage and the ringing on the waveforms are due to the resistance and capacitance of the probe used in the measurement. The amplitude of the switching voltages of the two transistors are the same and Figure 3b shows that the transistors are working in optimal Class E condition with a 180° phase delay. In Figure 3c, the voltage drop across R_L is shown. It can be seen that the amplitude is 13.75 V and is fairly a sinusoidal. The measured output power is 1.89 W or 4×0.47 W. The DC current drained from the power source is 0.46 mA (at 5 V). The efficiency is 82.2%. The loss is due to transistor CE resistance in ON & OFF states, the component loss, and the low Q factor of the resonator circuit causes some additional power loss.

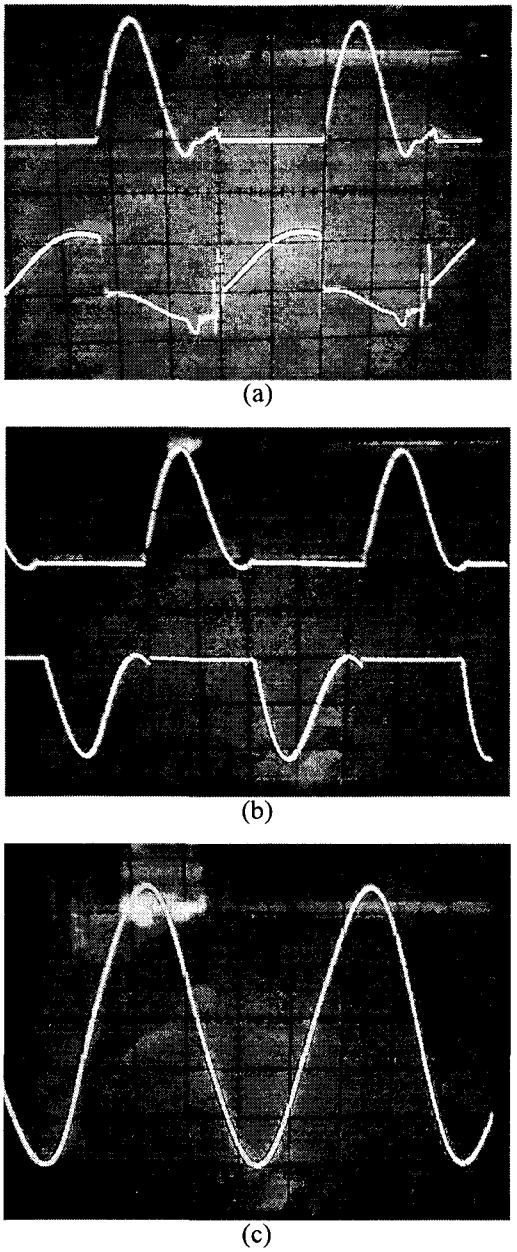


Figure 3. Measured waveforms at different locations. (a) Collector voltage and current of an individual transistor (The upper trace is the collector voltage at 10 V/div and the lower trace is the collector current at 0.5 A/div.). (b) Collector voltages of each transistor (5 V/div). (c) Output signal measured at R_L (5 V/div).

4. Conclusion

A Class E push-pull amplifier with high-output power is proposed. By employing the analytic method developed earlier [6], a completed theoretical background for the design are outlined. A 100-kHz class-E push-pull power amplifier is constructed to verify the design. The output power of this amplifier

is four times of that of a single-ended Class E amplifier with the same supply voltage.

4. References

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