Technical Article

Introduction to Switching-Mode Power Amplifiers: Class D Operation

4 days ago by Dr. Steve Arar

In this article, we'll learn the basics of switching-mode RF amplifiers in general and Class D amplifiers in particular.

In Class A, B, and C power amplifiers, a transistor acts as a controlled current source. As we move further down the alphabet, however, things change. The D, E, and F classes represent a completely different way of thinking in power amplifier design: instead of using the transistor as a current source, they operate it as a switch. Over the course of the next several articles in this series, we'll examine each of these three "switching-mode" amplifier classes.

In this article, we'll explore the basic principles of idealized Class D amplifiers and derive their output power and efficiency equations. We'll also briefly go over some non-idealities that degrade the performance of real-world Class D power amplifiers. Future articles will cover these non-idealities—and how to deal with them—in more detail.

Qualitative Operation of a Class D Amplifier

Figure 1 shows the schematic for a basic Class D amplifier.

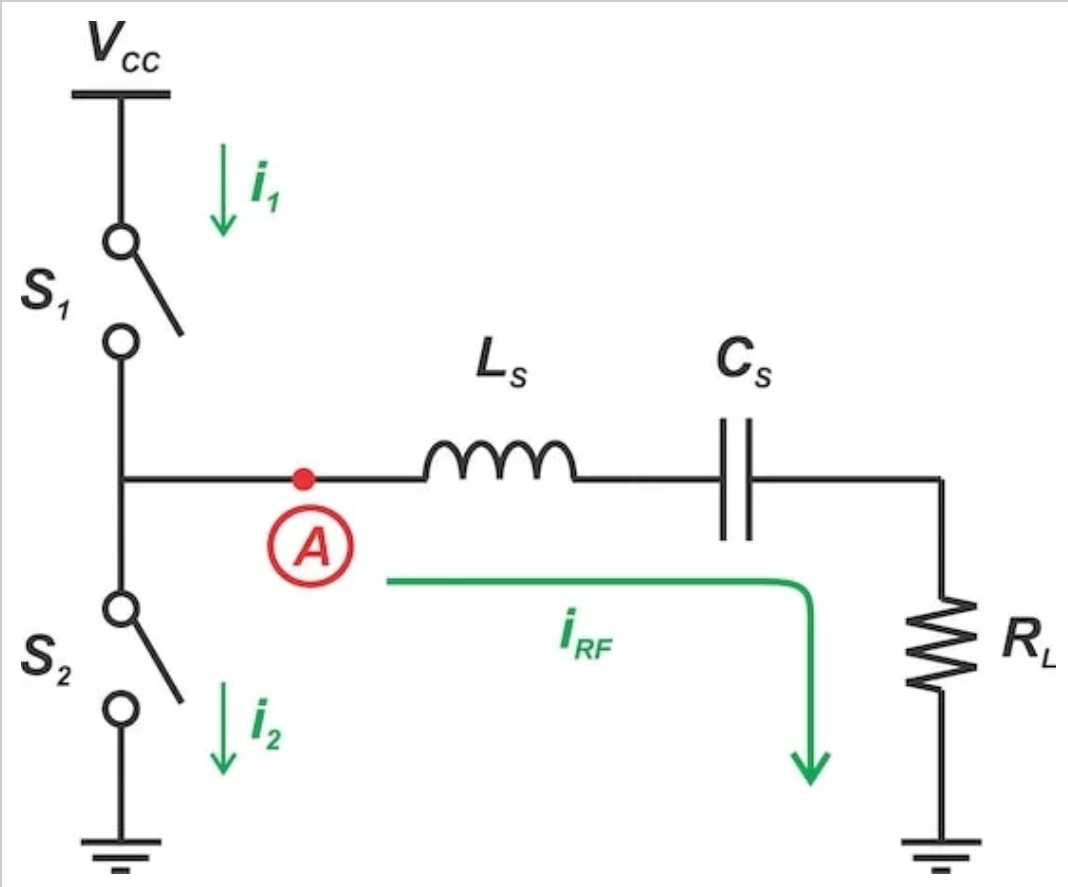

Figure 1. The basic Class D amplifier.

The two switches (S_1 and S_2) in this circuit operate such that when one is closed, the other is open. The switching action creates a rectangular waveform at node A, as shown in Figure 2.

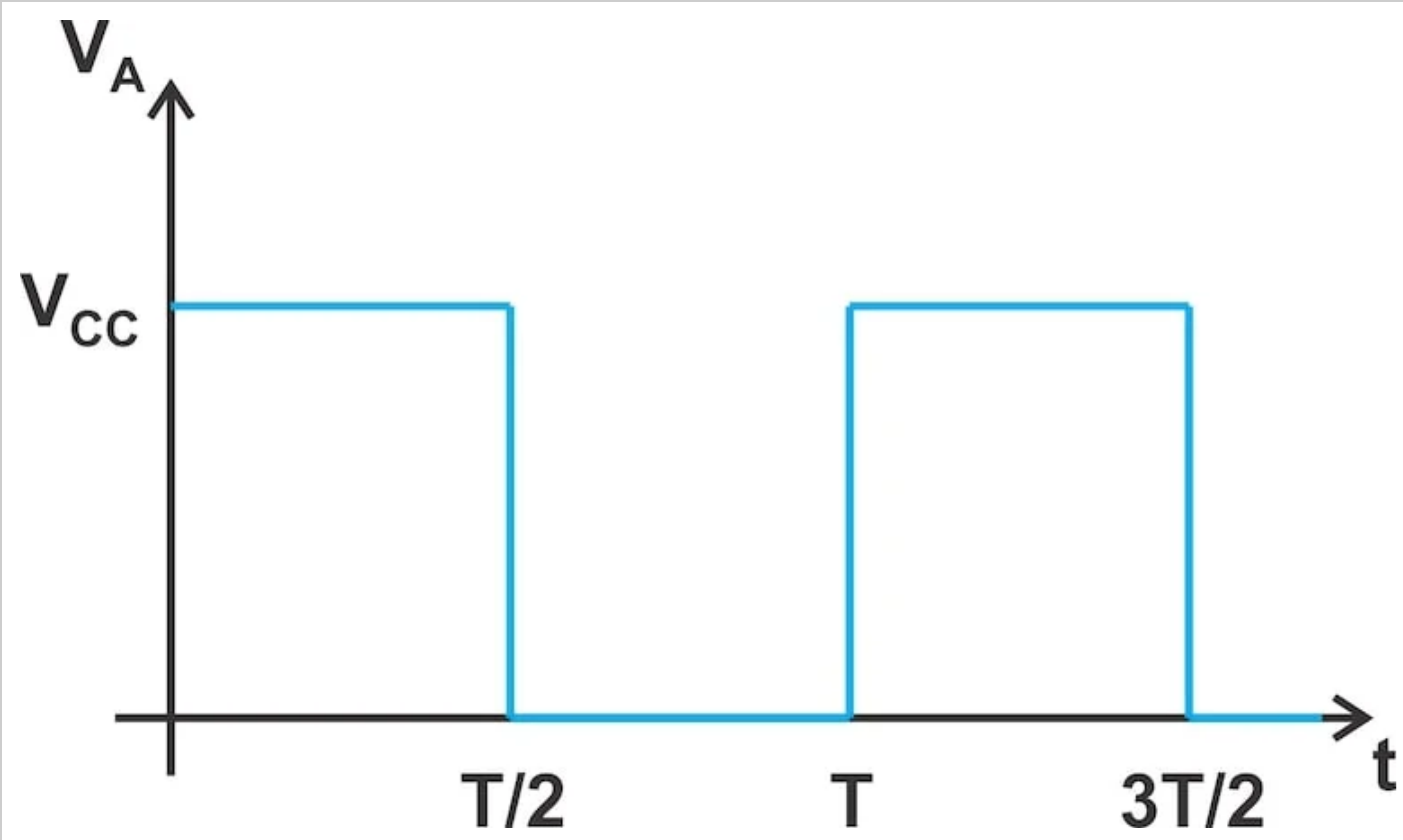

Figure 2. The square wave at the input of the series RLC circuit.

In a square wave with a 50% duty cycle, all odd harmonics (1st, 3rd, 5th, etc.) are present. The square wave is applied to a series resonant circuit tuned to the switching frequency. However, the series RLC circuit presents a very large impedance to all frequency components of the input voltage except the fundamental component. The tuned circuit blocks the flow of current at all harmonic frequencies and imposes a sinusoidal current at the fundamental frequency (Figure 3).

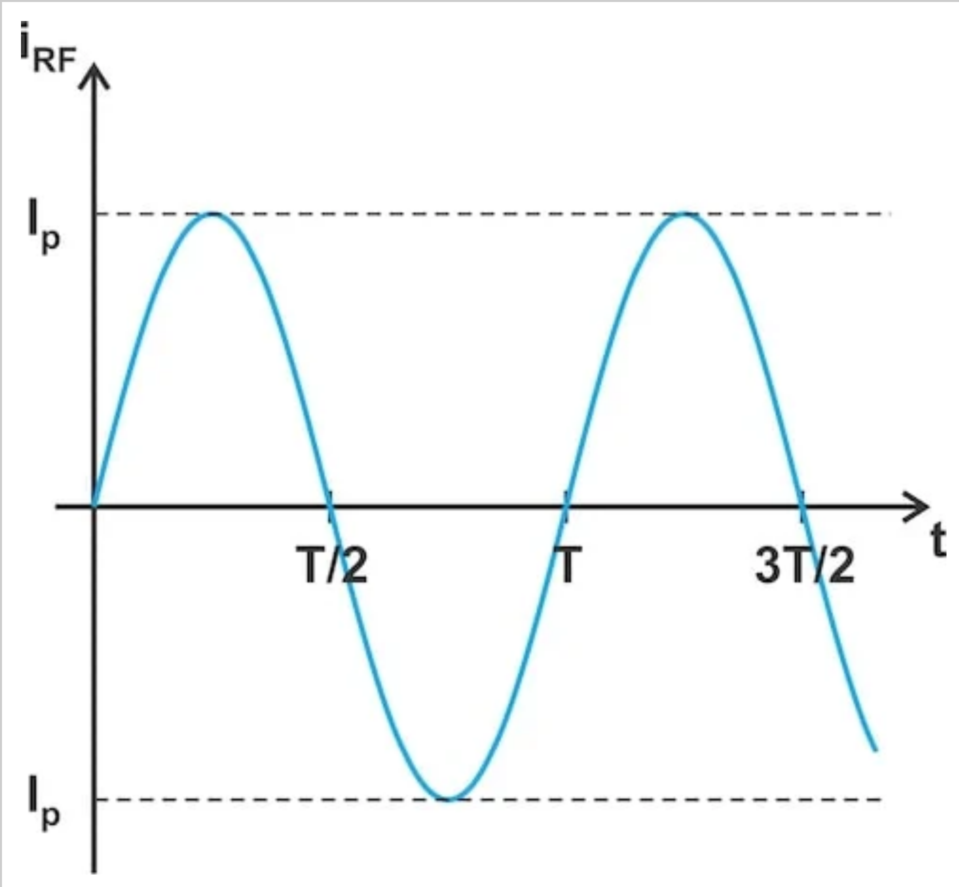

Figure 3. A sinusoidal current at the fundamental frequency flows through the RLC circuit.

Comparing Figures 2 and 3, we see that the switching-mode circuit in Figure 1 transfers AC power to the load at the same frequency as the switching frequency of the circuit. If an analog input signal is used to determine the switching frequency of the circuit, then the circuit is capable of delivering AC power at the frequency of the input signal. This is the basic function of an amplifier.

Please note that the amplifier in Figure 1 requires a series tuned circuit, not a parallel one. A parallel tuned circuit can't be used because it imposes a sinusoidal voltage, which conflicts with the square wave voltage created due to the switching action. A series tuned circuit, however, imposes a sinusoidal current through the load and seems to be consistent with the above qualitative description of the Class D amplifier's operation.

Calculating the Efficiency of the Class D Amplifier

An ideal switch dissipates no power because the product of its voltage and current is zero at all times. With the switch ON, it has no voltage drop; with the switch OFF, it has no current flow. Since the transistor dissipates no power, the theoretical efficiency of a switching-mode power amplifier should be 100%. Let's see if that holds true when we calculate the efficiency of the Class D amplifier in Figure 1.

To find the efficiency, we need to compare the power provided by the supply (P_{CC}) with the power delivered to the load (P_L) while current is flowing through the RLC circuit. We'll start by using the Fourier series representation to express the square wave voltage at node A in terms of its constituent frequency components:

$$V_A = \frac{V_{CC}}{2} + \frac{2V_{CC}}{\pi} \sum_{n=1}^{\infty} \frac{\sin((2n - 1)\omega_0 t)}{2n - 1}$$

Equation 1.

The series tuned circuit exhibits different impedances for each of these components. Most of the components see a very large impedance—ideally, an open circuit. Only the fundamental component sees a finite impedance of R_L.

Calculating the RF Current

From Equation 1, we know that:

- The fundamental component of the input voltage causes a current to flow through the RLC circuit.
- The fundamental component has a magnitude of $2V_{CC}/\pi$.

This gives us the following sinusoidal current:

$$i_{RF} = \frac{2V_{CC}}{\pi R_L} \sin(\omega_0 t)$$

Equation 2.

where $\frac{2V_{CC}}{\pi R_L}$ is the peak value (amplitude) of i_{RF}.

Calculating the Load Power

To find the average power delivered to the load, we use the following equation:

$$P_L = R_L i_{rms}^2$$

Equation 3.

where i_{rms} is the root-mean-square (RMS) value of the RF current. The current's RMS value is equal to its peak value (I_p) divided by $\sqrt{2}$, which would make $i_{rms}{}^2$ equal to $I_p{}^2/2$ in the equation above. Substituting in the value of i_p from Equation 2, we obtain:

$$P_L = R_L\left(\frac{4V_{CC}^2}{2\pi^2 R_L^2}\right) = \frac{2V_{CC}^2}{\pi^2 R_L}$$

Equation 4.

As an aside, Equations 3 and 4 rely on the load impedance being equal to the load resistance, (R_L). In RF circuits, that's usually assumed to be the case. The more generally applicable version of this formula is $P_L = |Z| i_{rms}^2 \cos(\theta)$, where |Z| is the magnitude of the impedance and θ is the impedance phase angle.

What we're using is just a simplified version of the above. R_L takes the place of |Z|, and we eliminate the cosine term because the phase angle of a resistive load impedance is 0 degrees.

Calculating the Supply Power

The next step toward finding the Class D amplifier's efficiency is determining the input power provided by the supply. The input power is equal to the supply voltage multiplied by the average value of the current drawn from the supply ($P_{CC} = V_{CC} I_{DC}$).

While the current flowing through the RLC circuit is a full sinusoid, the current through each of the switches is a half-wave rectified sinusoid. Figure 4(a) shows i_1, the current that flows through switch S_1. Figure 4(b) shows i_2, the current flowing through S_2.

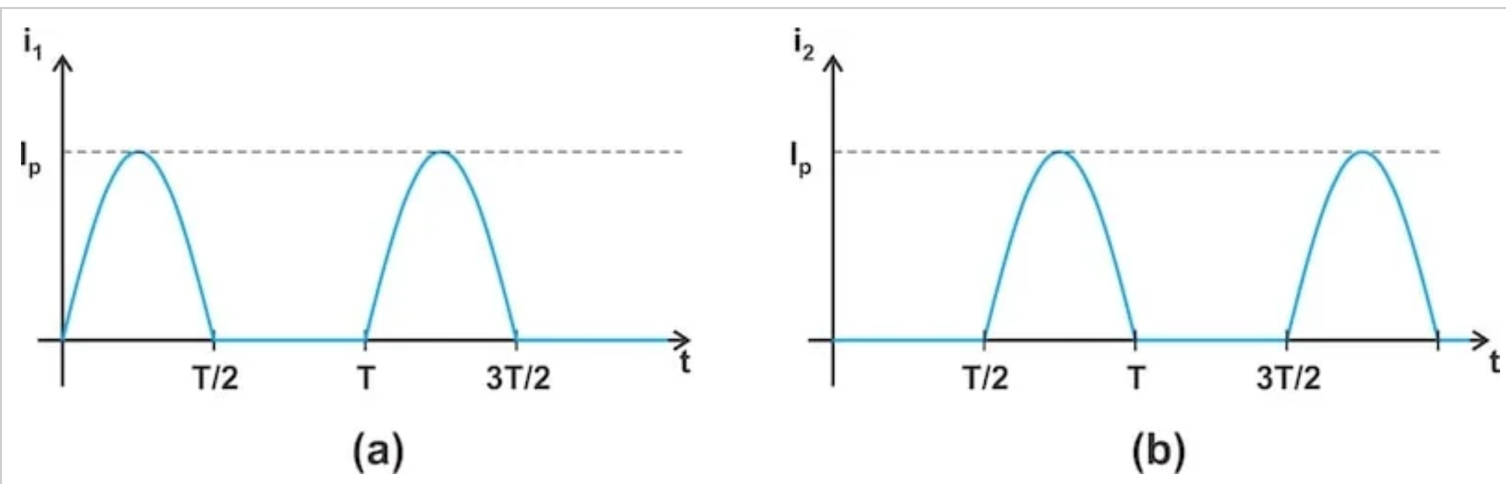

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Figure 4. The currents i_1 ***and*** i_2 ***flowing through the*** S_1 ***and*** S_2 ***switches, respectively.***

From Figure 1, we observe that the current drawn from the supply is i_1. Decomposing i_1 into a Fourier series yields:

$$i_1(t) = \frac{I_p}{\pi} + \frac{I_p}{2}\sin(\omega_0 t) - \frac{2I_p}{3\pi}\cos(2\omega_0 t) - \frac{2I_p}{15\pi}cos(3\omega_0 t) + \dots$$

Equation 5.

where I_p is the peak value of the current in Figure 4(a). The DC component of the current drawn from the supply is I_p/π, and therefore the power delivered by the supply is:

$$P_{CC} = V_{CC}I_{DC} = \frac{V_{CC}I_p}{\pi}$$

Equation 6.

Substituting for I_p from Equation 2, we obtain:

$$P_{CC} = \frac{2V_{CC}^2}{\pi^2 R_L}$$

Equation 7.

The power delivered to the load (Equation 4) is the same as that provided by the supply (Equation 7). The amplifier therefore has a theoretical efficiency of 100%, just as we predicted at the start of the section.

This is no big surprise. Although the voltage applied to the tuned circuit is a square wave, only the fundamental component produces a current in the RLC circuit. Therefore, the power associated with frequency components other than the fundamental is zero. Also, since the switch and the reactive components (L and C) are lossless, all power provided by the supply is delivered to the load.

To cement these concepts, let’s use the above equations to work through a brief example before we move on.

Example: Choosing Maximum Transistor Voltage and Current for a Class D Amplifier

Transistors have limitations on how much voltage, current, and power they can withstand without damage. Determine the maximum transistor current and voltage for a Class D amplifier that delivers 20 W to a 50 Ω load.

Substituting P_L = 20 W and R_L = 50 Ω into the output power equation (Equation 4), we obtain the supply voltage:

$$P_L = \frac{2V_{CC}^2}{\pi^2 R_L} \rightarrow 20 = \frac{2V_{CC}^2}{\pi^2 \times 50} \rightarrow V_{CC} = 70.2 \text{ V}$$

Equation 8.

This specifies the device voltage rating. Equation 2 shows that the maximum current through the transistors is:

$$I_p = \frac{2V_{CC}}{\pi R_L}$$

Equation 9.

All that's left is to plug in values for V_{CC} and R_L. Doing so results in:

$$I_p = \frac{2 \times 70.2 \text{ V}}{\pi \times 50 \ \Omega} = 0.89 \text{ A}$$

Equation 10.

The transistors have a maximum voltage of 70.2 V and a maximum current of 0.89 A.

Accounting for Non-Idealities

The simplified analysis in the preceding section assumes ideal switches with no voltage drop or resistance when they are ON, and infinite resistance when OFF. We also implicitly assumed that the switching occurs instantaneously, and hence without any power loss. In practice, neither of these assumptions hold true.

When a real-life switch is in the ON state and conducting current, power is dissipated by the switch resistance. The switching speed is also finite, leading to a non-zero *IV* product during transitions. Switching losses are why Class D and other switching-mode power amplifiers only function well at frequencies substantially below their transition frequency.

Non-ideal components affect the performance of Class D amplifiers in other ways as well. For example, a mistuned RLC circuit can introduce a reactive component to the load network. This doesn't affect the amplifier's efficiency, but it does reduce the output power. Reactive components in the load network also cause reverse currents to pass through the switches, necessitating the use of anti-parallel diodes.

We also need to consider the parasitic capacitances that appear at the input of the tuned circuit and the outputs of the switching transistors. These capacitances require additional power from the supply as they charge and discharge, reducing the efficiency of the amplifier.

Finally, if the Q-factor of the resonant circuit isn't high enough, harmonic components at the output may not be negligible. Additional filtering is then required to lower the harmonic components.

The Complementary Voltage-Switching Class D Amplifier

A practical Class D power amplifier needs to be a bit more complex than the ideal version in Figure 1. The simplest implementation of the Class D amplifier, known as the complementary voltage-switching circuit, appears in Figure 5.

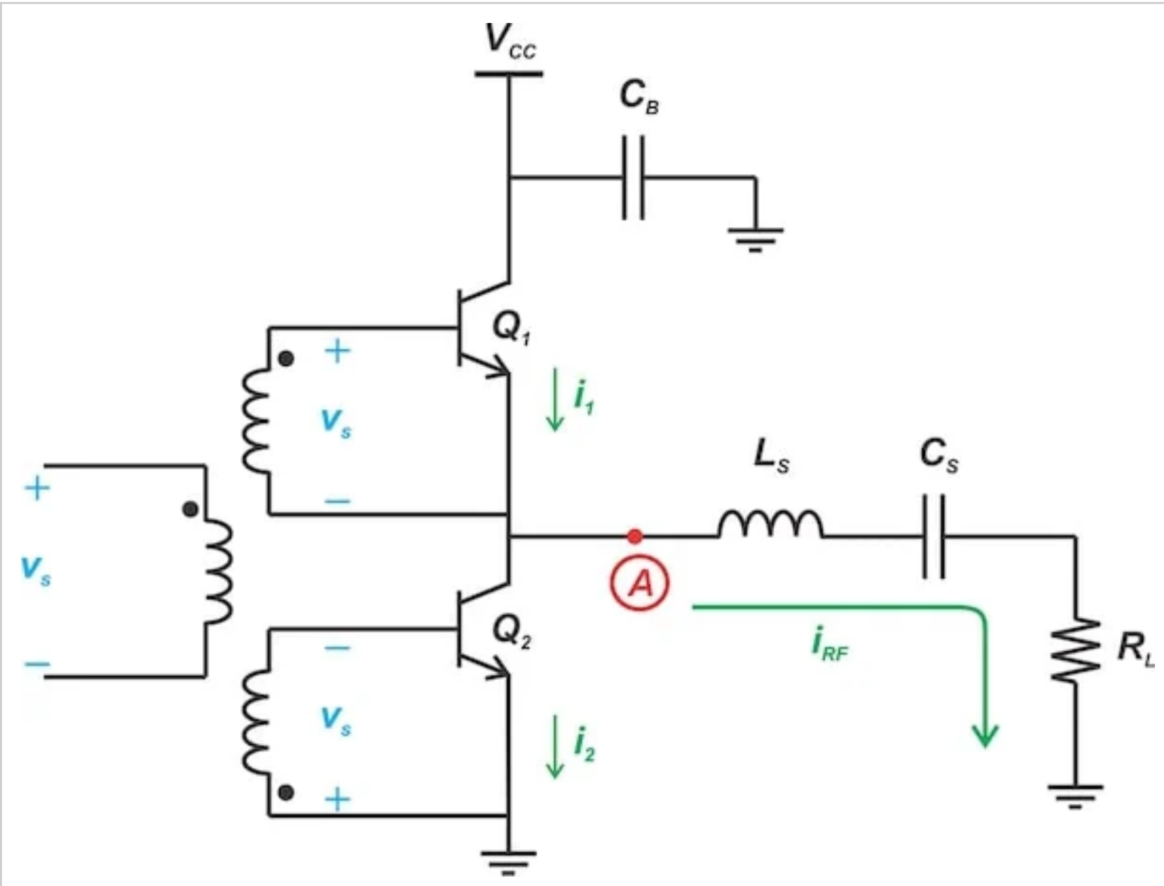

Figure 5. The complementary voltage-switching configuration.

In the above circuit, the transistors Q_1 and Q_2 are driven hard enough to make them act like switches rather than controlled current sources. To turn on only one of these transistors at a time, we use the transformer on the left side of the figure to produce signals of the opposite polarity from the input.

Finally, we saw in Figure 4 that the current drawn from the supply is a half-wave rectified sinusoid. A local bypass capacitor, which is labeled as C_B in Figure 5, is therefore required to supply the current pulses without incurring a significant voltage drop in the supply voltage.

Wrapping Up

Switching-mode power amplifiers achieve a high efficiency by employing active devices as switches rather than as controlled current sources. As we saw when examining Class D operation, the theoretical efficiency of an idealized switching-mode amplifier is 100%. However, moving from the theoretical to the practical requires us to consider non-idealities. In the next article, we'll learn why practical Class D amplifiers need anti-parallel diodes to handle mistuned RLC networks.

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