Technical Article

Class E Power Amplifiers: Waveform Engineering for Superior Performance

September 29, 2024 by Dr. Steve Arar

Class E RF amplifiers are designed to produce switch waveforms with a specific set of characteristics. In this article, we discuss the advantages and limitations of these waveforms.

In a sense, power amplifier design is the art of understanding and shaping waveforms to achieve high efficiency while also meeting acceptable levels of other specifications such as output power, linearity, and power gain. Class E power amplifiers, for example, seek to maximize efficiency by using a specially-designed load network to shape the switch voltage and current waveforms.

Figure 1, which we first saw at the end of the previous article, shows the typical switch waveforms of a Class E amplifier. The voltage and current transitions are displaced in time from each other, leading to non-overlapping waveforms.

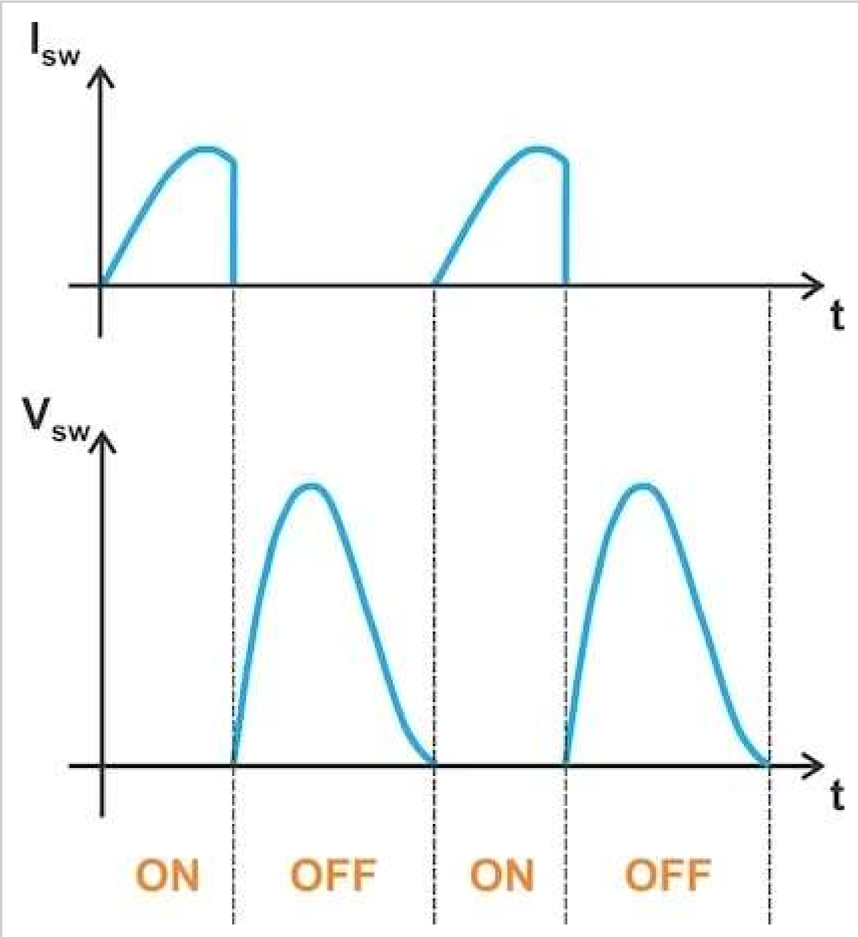

Figure 1. Typical switch current (top) and voltage (bottom) waveforms in a Class E RF power amplifier. Image used courtesy of Steve Arar

Note that the above waveforms are *typical*, not *ideal*. In this article, we'll explore the characteristics of the Class E amplifier's optimal waveforms, which are shown in Figure 2. After delving into what makes these waveforms desirable, we'll discuss an important limitation that renders them all but unachievable.

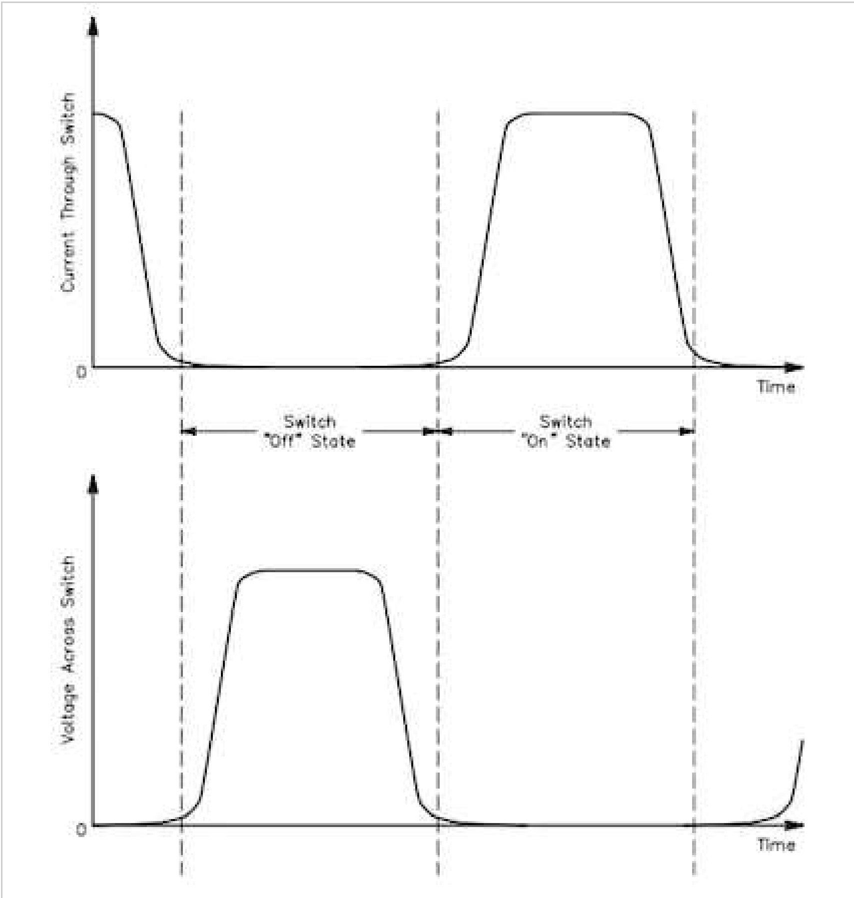

Figure 2. Target current (top) and voltage (bottom) waveforms for a Class E RF power amplifier. Image used courtesy of [Nathan O. Sokal](#)

Let's start by examining how these waveforms prevent power loss during both OFF-to-ON and ON-to-OFF transitions.

Important Characteristics of the Target Waveforms

In these waveforms, the voltage across the switch drops to zero ($V_{sw} = 0$) before the switch turns ON. At the moment the switch turns ON, the slope of the voltage is zero ($dV_{sw}/dt = 0$). Similarly, the current through the switch drops to zero ($I_{sw} = 0$) before the device turns OFF. At the turn-OFF instant, we have $I_{sw} = 0$ and $dI_{sw}/dt = 0$.

Eliminating Power Loss During Turn-ON Transitions

It's inevitable that parasitic capacitances will appear in parallel with a practical switch. Because of the drop to $V_{sw} = 0$, these capacitances hold no charge when the switch turns ON. This effectively eliminates the power loss that would otherwise result from discharging these capacitances.

The significance of a zero slope may not be as immediately apparent. However, the conditions $V_{sw} = 0$ and $dV_{sw}/dt = 0$ imply that V_{sw} remains at 0 V for some time before the switch turn-ON instant, thus ensuring an interval during which the switch can turn ON without causing power loss. Because of that, a slight mistuning of the amplifier won't significantly degrade efficiency. For those who are interested and have access to the IEEE database, the importance of the zero-slope condition is treated at greater length in "Class E—A New Class of High-Efficiency Tuned Single-Ended Switching Power Amplifiers" by Nathan O. Sokal and Alan D. Sokal.

It's also worth noting that the switch current in a Class E amplifier rises smoothly from zero once the switch turns ON. Since practical transistors have limited dI/dt capabilities, having the switch current rise from zero leads to shorter transition times.

Finally, the transistor's conductance increases gradually from zero as it switches from the OFF state to the fully ON state. Another way to think of this is that the switch resistance (R) reduces as it fully turns ON. Because the resistance is gradually decreasing at the same time current gradually increases, the I^2R power loss is minimized.

This is especially helpful when the turn-ON transition of the switch is slow. We can expect a Class E amplifier meeting the conditions $V_{sw} = 0$ and $dV_{sw}/dt = 0$ to have a small I^2R power loss even when the turn-ON transition time encompasses up to 30% of the RF cycle.

Eliminating Power Loss During Turn-OFF Transitions

We mentioned above that the current through the switch drops to zero ($I_{sw} = 0$) just before the device turns OFF. This prevents the unavoidable parasitic inductances that appear in series with the switch from undergoing abrupt current changes. Such jumps in the current waveform would lead to power loss during turn-OFF transitions, as we'll discuss shortly.

The conditions $I_{sw} = 0$ and $dI_{sw}/dt = 0$ at the switch turn-OFF instant imply that I_{sw} reaches 0 A for an interval prior to that instant. Like the voltage conditions during the OFF-to-ON transition, this reduces the degree to which slightly mistuning the amplifier reduces efficiency.

Limitations on Achieving Target Waveforms

The paper "Basic Limitations on Waveforms Achievable in Single-Ended Switching-Mode Tuned (Class E) Power Amplifiers" by Bela Molnar proves that the target waveforms in Figure 2 can't be achieved in a practical Class E amplifier. Molnar shows that it isn't possible to have zero voltage *and* zero current at both turn-OFF and turn-ON transitions of the switch if the circuit is to deliver non-zero output power to the load.

To have non-zero output power, we need a jump discontinuity in the voltage and/or current waveform. This is why the typical Class E waveforms provided in Figure 1, in which $V_{sw} = 0$ at the switching instants, show a jump discontinuity in current at switch turn-OFF. Let's examine how this leads to power loss.

The Effect of Non-Zero Current During Turn-OFF Transitions

Before continuing, please note that this section contains a lot of theoretical math. The key takeaway is that a non-zero switch current at the switch turn-OFF moment can cause power loss if there's an inductance in series with the switch. If you're interested in the calculus behind this, read on—otherwise, you may want to skip to the end of the section.

With that, let's move on to consider the simplified switching-mode amplifier in Figure 3. In this circuit diagram, L_2 is the effective inductance at the frequency of operation that appears in series with the switch. L_1 approximates an open circuit at RF.

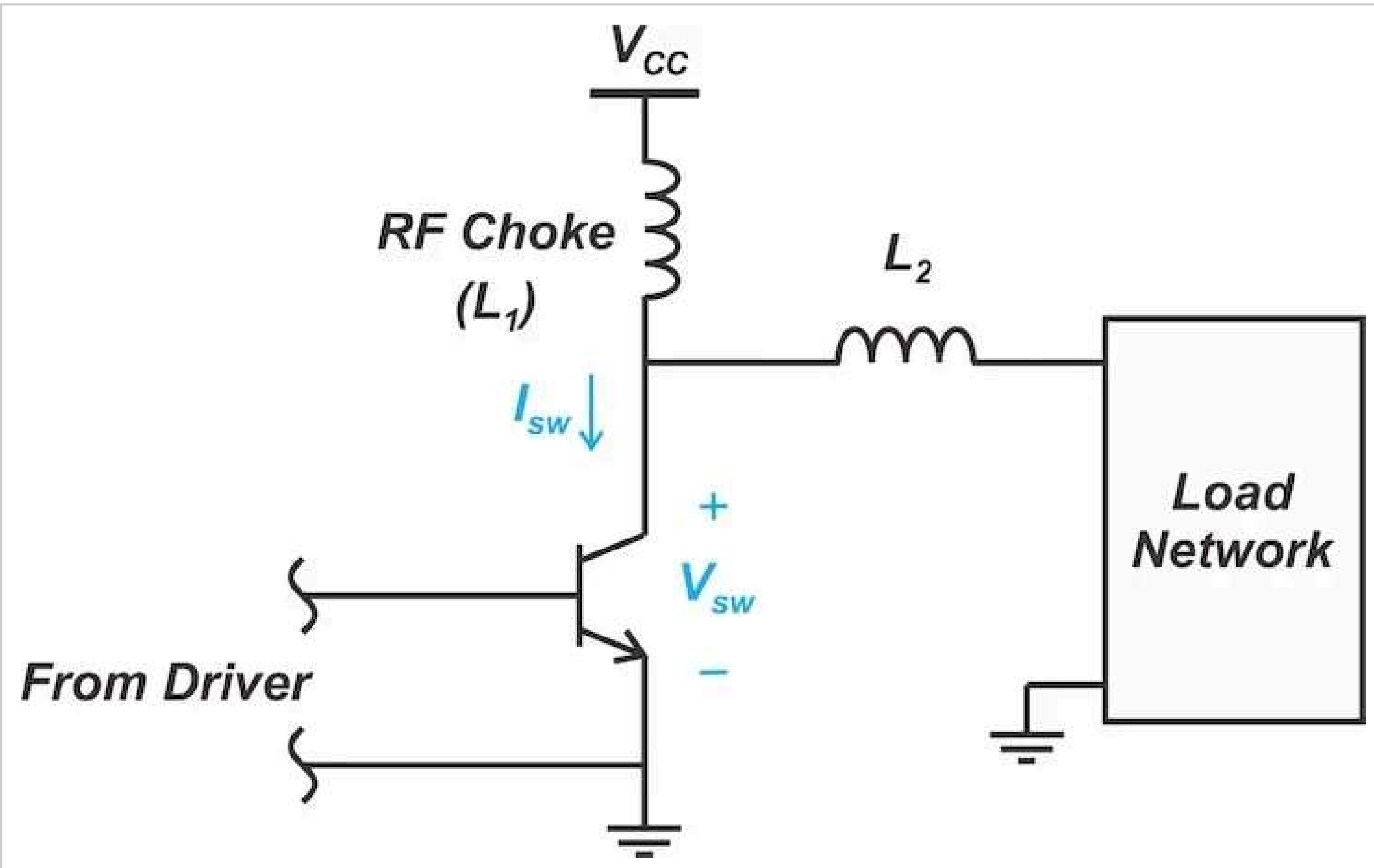

Figure 3. A simplified switching-mode power amplifier with inductance L_2 ***appearing in series with the switch. Image used courtesy of Steve Arar***

Suppose that the switch in Figure 3 turns OFF at $t = t_0$. The switch current and voltage waveforms at this instant are shown in Figure 4.

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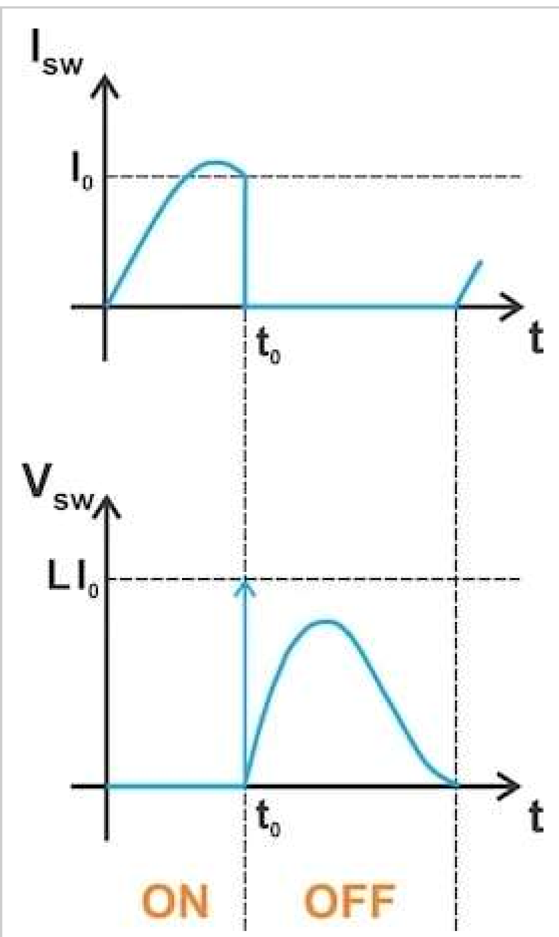

Figure 4. The current through the switch (top) and the voltage across it (bottom). Image used courtesy of Steve Arar

In the figure above, the current passing through the inductor has a non-zero value of I_0 until t_0^-. At $t = t_0$, the current is still I_0; after t_0^+, it's zero. Current in an inductor can't change instantaneously unless an impulse voltage—Dirac's delta function δ(t)—is applied or supported in the circuit. This can be understood by noting that the integral of the unit impulse function δ(t) over time is a unit step function (a jump in the waveform).

In other words, differentiating a waveform that has a jump discontinuity results in an impulse function within the derivative waveform. Since the voltage across an inductor (v) is proportional to the derivative of its current:

$$v = L\frac{di}{dt}$$

Equation 1.

we conclude that a jump in the inductor current leads to an impulse function in the inductor voltage waveform. Note that we're only interested in the circuit's behavior at the switching instant ($t = t_0$). The voltage waveform after $t = t_0$ is determined by the load network and is a topic for another day.

From Equation 1, it can be shown that a jump from I_0 to 0 A corresponds to a voltage impulse of amplitude LI_0 across the inductor. Assuming that this entire voltage spike appears across the switch, we obtain the voltage waveform shown in the lower half of Figure 4. In this curve, the arrow-terminated vertical line illustrates an impulse function of amplitude LI_0.

To calculate the instantaneous power loss at $t = t_0$, we need to know both the switch voltage and current. The product of these two quantities gives us the power loss:

$$P_{dissipated} = V_{sw} I_{sw}$$

Equation 2.

From the above discussion, we know that V_{sw} is equal to $LI_0\delta(t - t_0)$. However, we still need to find I_{sw}.

Since the switch current changes from I_0 to zero at $t = t_0$, we can describe I_{sw} at this instant as the average of the left-hand and right-hand limits at the point of discontinuity. We therefore have:

$$I_{sw}(t = t_0) = \frac{1}{2}(I_0 + 0) = \frac{I_0}{2}$$

Equation 3.

Substituting Equation 3 into Equation 2, we find the instantaneous power dissipated in the switch at $t = t_0$:

$$P_{dissipated} = LI_0 \times \frac{1}{2}I_0 = \frac{1}{2}LI_0^2$$

Equation 4.

Dividing this value by the time duration (T) of one RF cycle gives us the average power dissipated in the switch:

$$P_{ave} = \frac{1}{2}LI_0^2 \times \frac{1}{T} = \frac{1}{2}fLI_0^2$$

Equation 5.

where f is the switching frequency.

The Class E Zero-Current Switching Amplifier

The circuit we've been examining is known as the Class E zero-voltage switching (ZVS) amplifier. There are also Class E zero-current switching (ZCS) amplifiers, so called because they have zero current at the switching instants. Instead of a jump in the current waveform when the switch turns OFF, they exhibit a jump in the voltage waveform when the switch turns ON. This is illustrated in Figure 5.

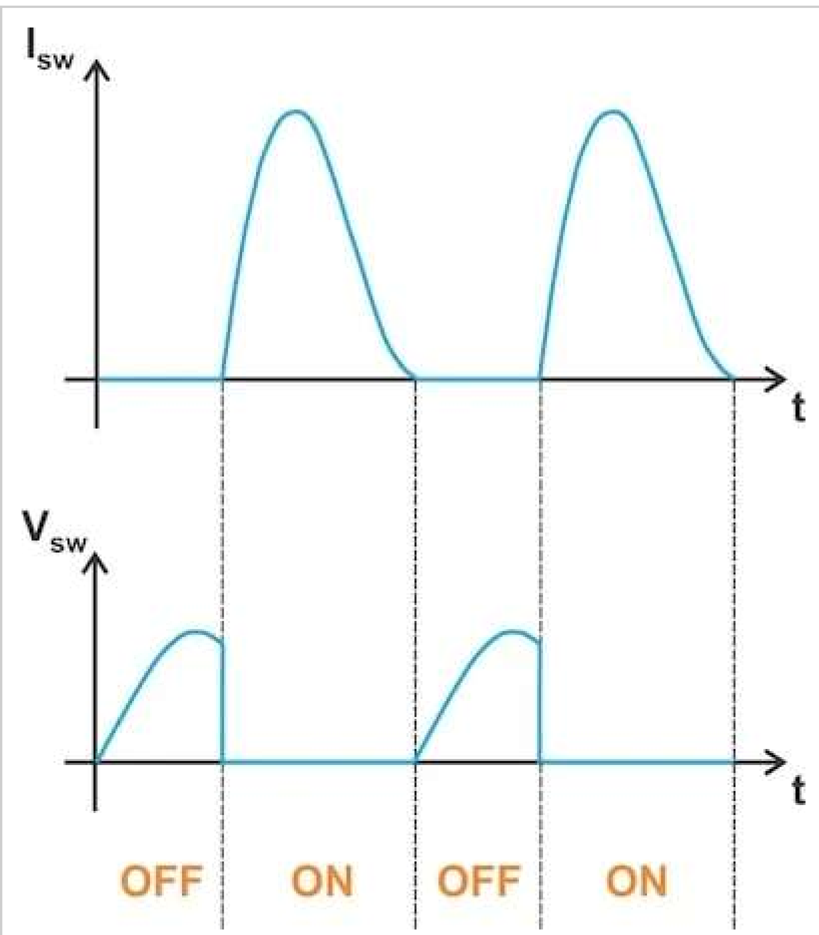

Figure 5. Class E waveforms with a jump discontinuity in voltage at the switch turn-ON instants. Image used courtesy of Steve Arar

ZCS amplifiers are usually less attractive than ZVS amplifiers for practical applications—especially at high frequencies—because they require a switch with negligible capacitance. If the switch capacitance is appreciable, an abrupt change in the voltage will result in power loss when the switch turns ON.

Wrapping Up

In the next article, we'll examine the load networks and transient responses of Class E amplifiers. We'll then go over some design equations that will allow us to easily choose component values for a Class E stage. Note that our focus will once again be on the ZVS amplifier, though we may return to the ZCS circuit later on in the article series.

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