A Comprehensive Study of Power Amplifier Classes: Design Parameters and Efficiency Analysis with a Focus on Class E PA

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Abstract

Power amplifiers are classified in this study into classes A, B, C, D, E, AB, and F based on their unique operating traits and performance measures. The primary objectives are to investigate the key parameters and to present experimental results using MATLAB to evaluate their performance. The Class E power amplifier, which presents a fresh method to high-efficiency switching amplifiers, is a major emphasis. N. O. Sokal and A. D. Sokal introduced building circuit models, modelling performance under controlled settings, and comparing linearity, efficiency, and power output were all part of the technique. This study offers a fundamental framework for the selection and design of high-efficiency power amplifiers for a variety of applications, such as wireless communications and audio systems, and offers insightful information for both academic and industry applications.

Keywords: Power amplifiers, classes of power amplifiers, design parameters

1. Introduction

Power amplifiers are like especial tools that help make electronic devices stronger by boosting their signals. These essential components are categorized into various types, each distinguished by its unique operational features, energy efficiency, and specific use cases. There are different types of power amplifiers that each has its advantages and disadvantages in terms of effectiveness and energy usage. These different classes cater to a wide spectrum of requirements in audio, radio frequency, and other signal processing domains, allowing engineers to select the most suitable amplifier design for their specific needs [8].

Class A amplifiers provide high linearity and low distortion, making them ideal for applications requiring high-fidelity audio and precise instrumentation. However, they are inefficient in terms of power usage. Class B and class AB amplifiers provide improved efficiency at the cost of potential distortion, finding applications in audio systems and RF transmitters. Class C amplifiers, while highly efficient, are limited to RF applications due to their non-linear nature. Class D amplifiers utilize pulse-width modulation to achieve high efficiency, particularly useful in digital audio and battery-operated devices [1] [8].

Class E and Class F power amplifiers are designed for superior RF signal transmission. Class E amplifiers are known for their high efficiency, utilizing a single-pole switching device and a precisely tuned reactive network to minimize power dissipation during the switching process. When compared to conventional Class B or Class C amplifiers, Class E amplifiers can achieve much greater efficiency, often reducing power losses by up to 2.3 times when the same transistor is used at the same frequency and power level [1][7][8].

Different power amplifier classes present unique advantages and disadvantages in terms of efficiency, linearity, complexity, and their suitability for various applications, catering to a wide range of needs in both the audio and wireless communication sectors. Understanding these class distinctions is crucial for selecting the appropriate amplifier for a specific application.

This study investigates general classes of power amplifiers, providing an overview of their characteristics and discussing key parameters affecting their efficiency. Various circuit configurations were constructed, and their performance was analyzed experimentally using MATLAB. The focus is particularly directed towards the Class E amplifier, with a comprehensive discussion of its mechanisms, design formulas, and enhancement methods [8].

The main goals of this study include:

- To offer a detailed explanation of the fundamental operating mechanisms for each significant class of power amplifiers.
- To analyze and compare the efficiency, linearity, and power output capabilities across different amplifier classes
- To conduct an in-depth examination of Class E amplifiers, including their design equations and optimization techniques
- To present simulation results that illustrate the performance characteristics of various amplifier classes
- To discuss the implications of our findings for power amplifier selection and design in modern electronic systems

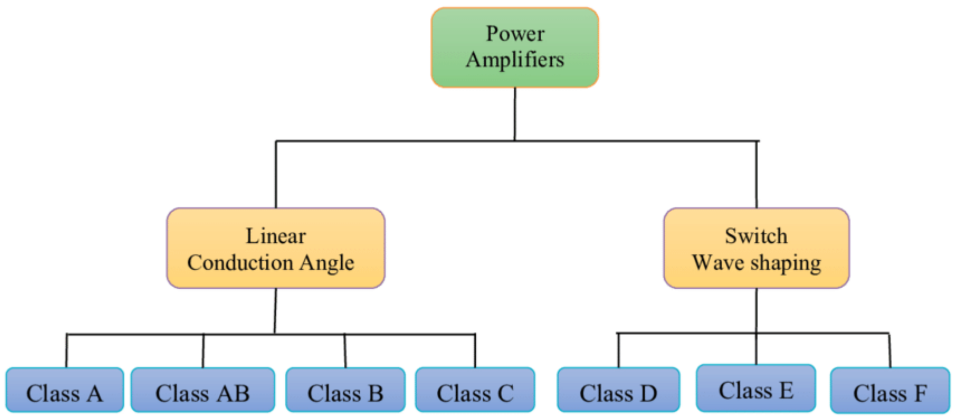


Figure 1. *Types of Power Amplifiers*

2. Class A Amplifier

In a Class A circuit, a single transistor serves as the active device and remains continuously conducting, allowing current to flow throughout the entire input waveform cycle. This constant operation enables the Class A amplifier to achieve excellent linearity and high-frequency response. However, this configuration has significant drawbacks, primarily high power consumption, and excessive heat generation, due to the transistor's continuous conduction [7]. Class A amplifiers, while known for their high-quality output, suffer from relatively low energy efficiency. In conventional setups, they typically convert only about a quarter to a third of their input power into useful output. Although this efficiency can be boosted to around 40-50% by employing inductively coupled outputs, Class A amplifiers still lag behind other amplifier classes in terms of power utilization. This inherent inefficiency is a significant trade-off when considering Class A designs for power-sensitive applications [3]. Due to these limitations, Class A amplifiers are generally best suited for low-power applications where signal fidelity is crucial, such as high-quality audio preamplifiers or small-signal amplification stages. An ideal Class A amplifier circuit configuration is depicted in Figure 2.

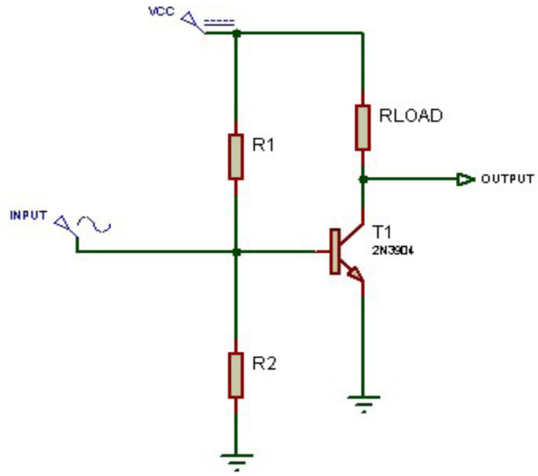


Figure 2.*Class A Amplifier*

3. Class B Amplifier

Class B amplifier designs provide higher efficiency than Class A configurations. This circuit contains two interoperable transistors, sharing input signal processing between them. The first transistor amplifies the positive half-cycle, and the opposite transistor processes the negative half-cycle to restore the overall shape of the output signal. This push-pull configuration significantly minimizes power consumption [8]. A popular implementation of this concept is the push-pull configuration, which effectively combines the outputs of two transistors. When optimized, Class B amplifiers can achieve efficiency levels of up to 78.5%. This represents a significant improvement over Class A designs in terms of power utilization [1] [8].

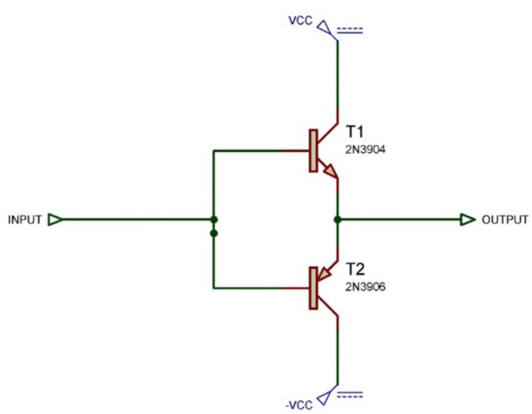


Figure 3. *Class B Amplifier*

However, Class B amplifiers face a notable challenge: cross-over distortion. This distortion occurs at the transition point between the two transistors' conduction periods, creating a region of non-linearity this design, while efficient, has a notable drawback. During the transition between transistors, a brief period occurs where neither component is fully operational. This momentary gap in conduction can introduce distortion into the output signal, potentially compromising audio quality. To address this limitation, engineers developed the Class AB amplifier. This hybrid approach seeks to preserve the efficiency gains of Class B while minimizing the distortion issues, striking a balance between power conservation and signal fidelity[3][8].

4. Class AB amplifier

The class AB amplifier emerged as a compromise solution that solved the cross-distortion problem characteristic of class B amplifiers. This hybrid approach aims to blend the best aspects of both Class A and B designs, balancing the superior linearity of the former with the improved efficiency of the latter. This configuration employs two transistors working in tandem, with each one processing alternating halves of the incoming waveform. This configuration allows for a smoother transition between the conducting states of the transistors, helping to mitigate distortion while maintaining relatively high efficiency. However, unlike in Class B, each transistor is biased to remain slightly active even when not handling its primary half-cycle. This overlap in conduction periods ensures that the transistors do not completely turn off during the crossover point, effectively minimizing cross-over distortion [1][3].

Class AB amplifier designs primarily come in two forms: those utilizing complementary transistor pairs and those employing an offset line arrangement. The complementary design allows for flexibility in signal input, with options to feed the signal directly to both transistor bases or to introduce it between biasing diodes. Figures 4(a) and 4(b) show these different input arrangements for the Class AB amplifier. Additionally, Figure 4(c) shows an offset configuration, which can be powered by either a dual or single supply [7][8]. These various configurations offer flexibility in design, allowing engineers to optimize the amplifier for specific applications while maintaining the benefits of reduced distortion and improved efficiency.

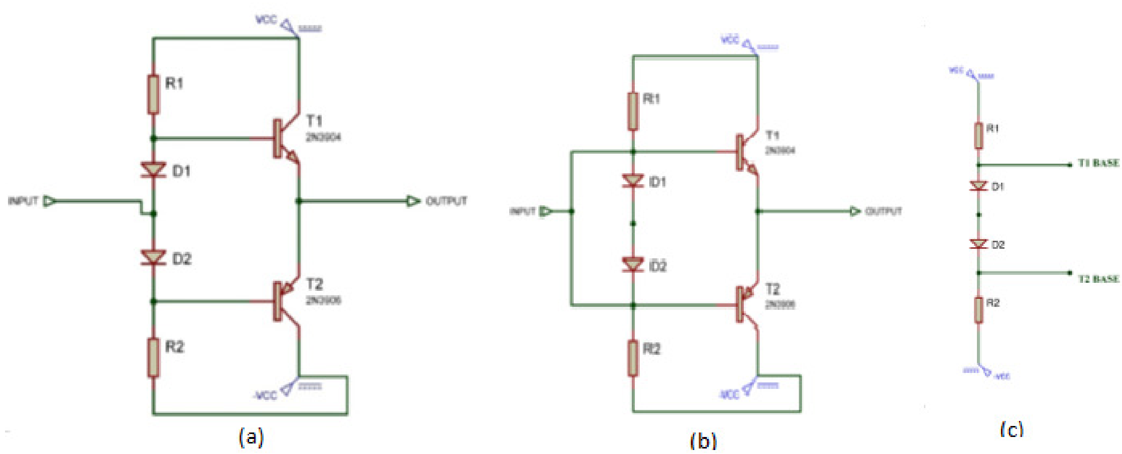


Figure 4. *Class AB amplifier with different input and offset configurations*

5. Class C Amplifier

A Class C amplifier uses a single transistor as a switching device, which conducts for less than half the period of the input waveform. This mode of operation causes significant distortion, but allows a high efficiency, which theoretically is up to 90%. Because of this inherent distortion, Class C amplifiers are unsuitable for audio applications, but are widely used in RF applications such as RF oscillators and amplifiers [3]. Figure 5 illustrates the common circuit configuration of a Class C amplifier [7]. The biasing resistor RB places the Q point (Operating point) of the transistor below the cut-off point, ensuring conduction only when the input signal amplitude exceeds the sum of the base-emitter voltage and the bias voltage. This structure does not provide an output signal if these conditions are not met [7]. The main component of a class C amplifier is a tank circuit consisting of an inductor L1 and a capacitor C1, which isolates the desired signal. The values of L1 and C1 are chosen to match the resonant frequency of the input signal [8]. When properly tuned, this resonant circuit will oscillate at the desired frequency while attenuating others [2].

The resonant frequency is determined by the relationship between L1 and C1, typically expressed as $f = 1 / (2\pi\sqrt{(L1C1)})$, where f is the resonant frequency in Hz, L1 is in Henries, and C1 is in Farads.

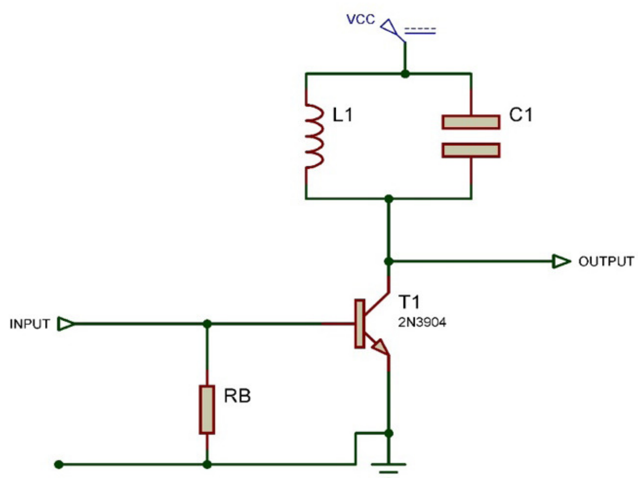


Figure 5.*Class C Amplifier*

6. Class D Amplifier

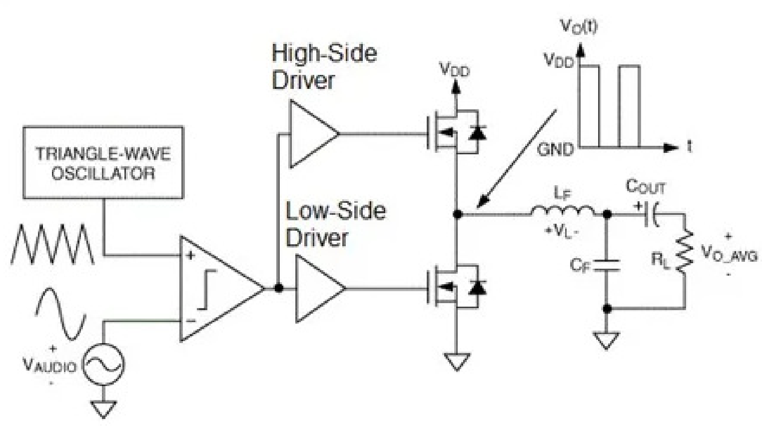


Figure 6.*Class D Amplifier*

Class D amplifiers employ a unique approach, utilizing pulse-width modulation (PWM) in conjunction with a triangular or saw tooth waveform generator. This design typically includes a PWM module, a pair of output MOSFETs, and an external low-pass filter for signal reconstruction structure shown in Figure 6. The MOSFETs function as switches, alternately connecting the output to the power supply and ground, creating a high-frequency square wave. This wave is modulated based on the input audio, achieved by comparing it with an internal reference wave. The resulting square wave's duty cycle directly corresponds to the input signal amplitude, defaulting to 50% when no input is present. By operating transistors in fully on or off states, Class D amplifiers achieve high efficiency. The final low-pass filter removes the high-frequency components, leaving only the amplified audio signal [10].

7. Class F Power Amplifier

Class F power amplifiers are very efficient switching amplifiers used at radio frequencies. Figure 7 shows the basic design architecture of a class F power amplifier. VDD and VGG refer to the respective drain and gate bias voltages generated by the 26 V. DC bias and DC blocking were omitted from this design. The input and output networks change the impedance to ensure that the transistors on each side have a total of 50 ohms. At the fundamental frequency, the L0C0 filter combination is tuned to give harmonic frequencies a very high impedance (ideally open circuit) and at the same time a very low impedance (ideally short circuit). L3 and C3 together form a third harmonic trap, creating a high impedance to the third harmonic and allowing other signals to pass through. As a result, third harmonic voltages add phase to the fundamental drain voltage, resulting in a flattened drain voltage waveform. A series L2C2 filter combination with a bypass capacitor directs the second harmonic to the ground and provides high impedance at other frequencies. This causes the second harmonic current to short circuit, resulting in a drain current waveform similar to a peak half-sine wave [1][2][3].

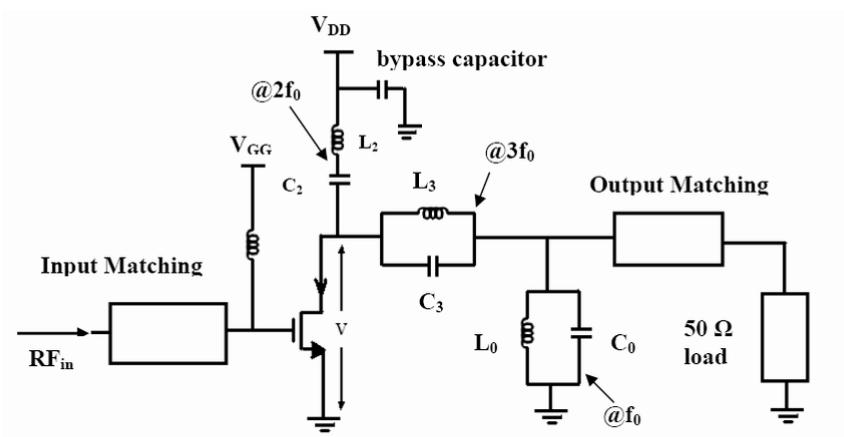


Figure 7.*Class F Amplifier*

8. Class E power Amplifier

Class E amplifiers represent a very efficient switching power amplifier used at radio frequencies. These amplifiers use a transistor as an on/off switch and carefully modify the voltage and current waveforms to minimize power loss, especially during switching transitions. Compared to traditional Class B or Class C amplifiers, Class E amplifiers can achieve significantly higher efficiency - typically 2.3 times less power loss when using the same transistor at the same frequency and output power. The Class E amplifier has a single pole switching element and a tuned reactive network between the switch and the load. This configuration allows switching to occur at zero current (on to off) or zero voltage (off to on), which minimizes switch power losses [17].

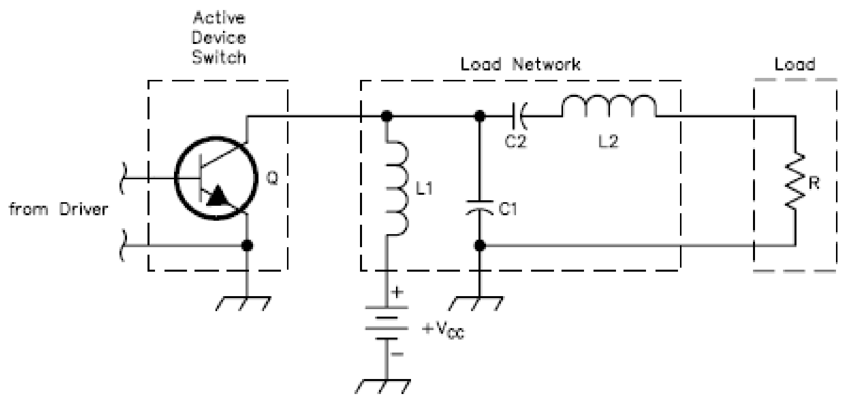


Figure 8. *Class E Power Amplifier*

The circuit diagram of a Class E power amplifier is depicted in Figure 8. The design equations are derived under the following assumptions [11][17].

- The RF choke permits a nearly constant DC without any parasitic resistance.
- The series resonant circuit exhibits a high-quality factor, ensuring a purely sinusoidal output current at the operating frequency.
- The shunt capacitance remains unaffected by the collector/drain voltage.
- Switching losses in the transistor are negligible, indicating soft switching operation.

Detailed derivation of output power and efficiency is complex and referenced elsewhere [11]. This work provides optimal values for drain susceptance, series inductance, and load resistance tailored to specific output power requirements. Essential formulas necessary for design can be found in references [11] and [13].

$$R_L = \frac{0.577V_{dd}^2}{P_{out}} - - - - - - - - - \quad (1)$$

(or)

$$P_{out} = \frac{0.577V_{dd}^2}{R_L} - - - - - - - - - - (2)$$

and

$$L_{opt} = \frac{1.154\ R_L}{2\pi f} - - - - - - - - \quad (3)$$

$$C_{opt} = \frac{0.1836}{2\pi f R_L} - - - - - - - - - - \quad (4)$$

Where RL represents the total resistance of the transistor and Vdd is the DC source voltage, Lres and Cres represent the inductance and capacitance in the series resonant circuit.

The design process for a Class E power amplifier is as follows:

Start by determining the load resistor. Both the load resistance and Vdd are limited by the specified output power requirement. To achieve optimal efficiency, the highest possible Vdd is used [12]. After that, the value of the load resistance is calculated using the formula.

The values of Lres and Cres depend on the loaded quality factor of the resonant network. The loaded quality factor is defined as the ratio of the energy stored in the reactive components to the average power dissipation of the resonant circuit. This serves as a critical assessment of reactive components and affects both bandwidth and power dissipation. A higher quality factor results in narrower bandwidth and lower average power dissipation [14].

To determine the values of the series resonant components, the loaded quality factor of the power amplifier is chosen based on the desired bandwidth and acceptable power losses. Typical practical values of Q vary between 3 and 10 [5]. The values of Lres and Cres are then calculated using the definition of quality factor in reference [14].

$$L_{res} = \frac{Q_1 R_L}{2\pi f} - - - - - - - - - - (5)$$

$$C_{res} = \frac{1}{2\pi f Q_1 R_L} - - - - - - - - - - (6)$$

$$\omega_{res}^2 = (2\pi f)^2 = \frac{1}{L_{res} C_{res}} - - - - - - - - - - (7)$$

$$\omega_{res} = \frac{1}{\sqrt{L_{res} C_{res}}} - - - - - - - - - - (8)$$

The optimal inductance is determined based on the fact that the current is in phase with the zero-voltage switching voltage (ZVS) [11]. The shunt capacitance is designed to keep the voltage zero during the transient. The shunt capacitance value is calculated with two conditions: the switch voltage is zero when $t = \pi/2\omega$, and the derivative of the switch voltage is zero when $t = \pi/\omega$ [11].

The parasitic capacitance from the drain to the source also affects the calculated total capacitance, as shown in Figure 4.1. The size of the transistor is determined based on the Copt. In practice, the design cannot be idealized due to the parasitic characteristics of the circuit components [15], [16].

A class comparison of design parameters is given in Table 1. Table 2 shows the design parameters of a Class E power amplifier.

Table 1. *Comparison between design parameters in PA*

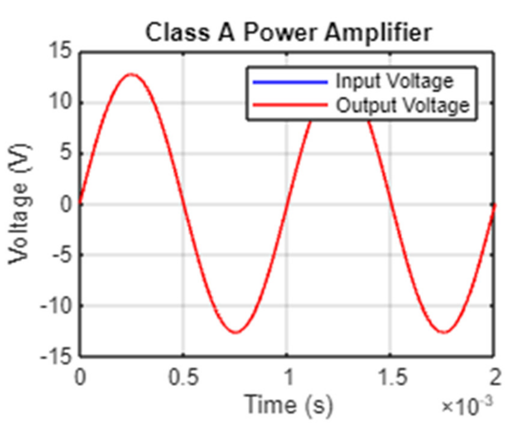
Design Parameters	Class A	Class B	Class C	Class AB	Class D
Supply Voltage (V)	15.00	15.00	15.00	15.00	15.00
Output Power (W)	10.00	10.00	10.00	10.00	10.00
Load Resistance (Ω)	8.00	8.00	8.00	8.00	8.00
DC Current (A)	0.67	0.33	2.67	0.67	-
Peak Output Voltage (V)	12.65	12.65	12.65	12.65	12.65
Peak Output Current (A)	1.58	1.58	1.58	1.58	1.58
Efficiency (%)	50	78.5	90	50-78.5	100

Table 2. *Class E PA Design Parameters*

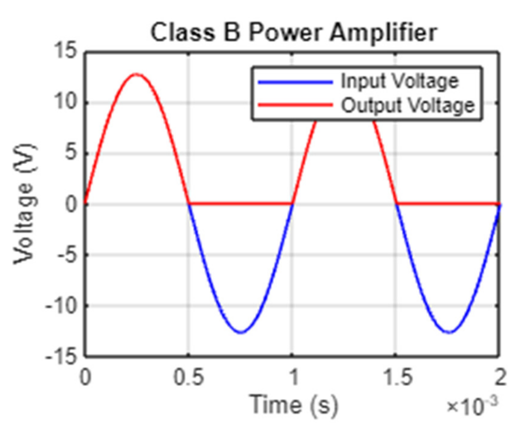
DesignParameters	Values
Operating frequency(MHz)	1.00
Supply voltage(V)	15.00
Load resistance(Ohms)	8.00
Output power(W)	10.00
Peak switch voltage(V)	53.40
Peak switch current(A)	1.91
Choke inductance (L1)(μH)	3.82
Shunt capacitance (C1)(þF)	6631.46
Series inductance (L2)(μH)	1.12
Series capacitance (C2)(þF)	2387.32

9. Results and discussions

Figure 9 (a), (b), (c), (d), (e) and (f) show the input and output voltages of different classes of power amplifiers. These curves have voltage along the Y axis and time along the X axis.



(a)



(b)

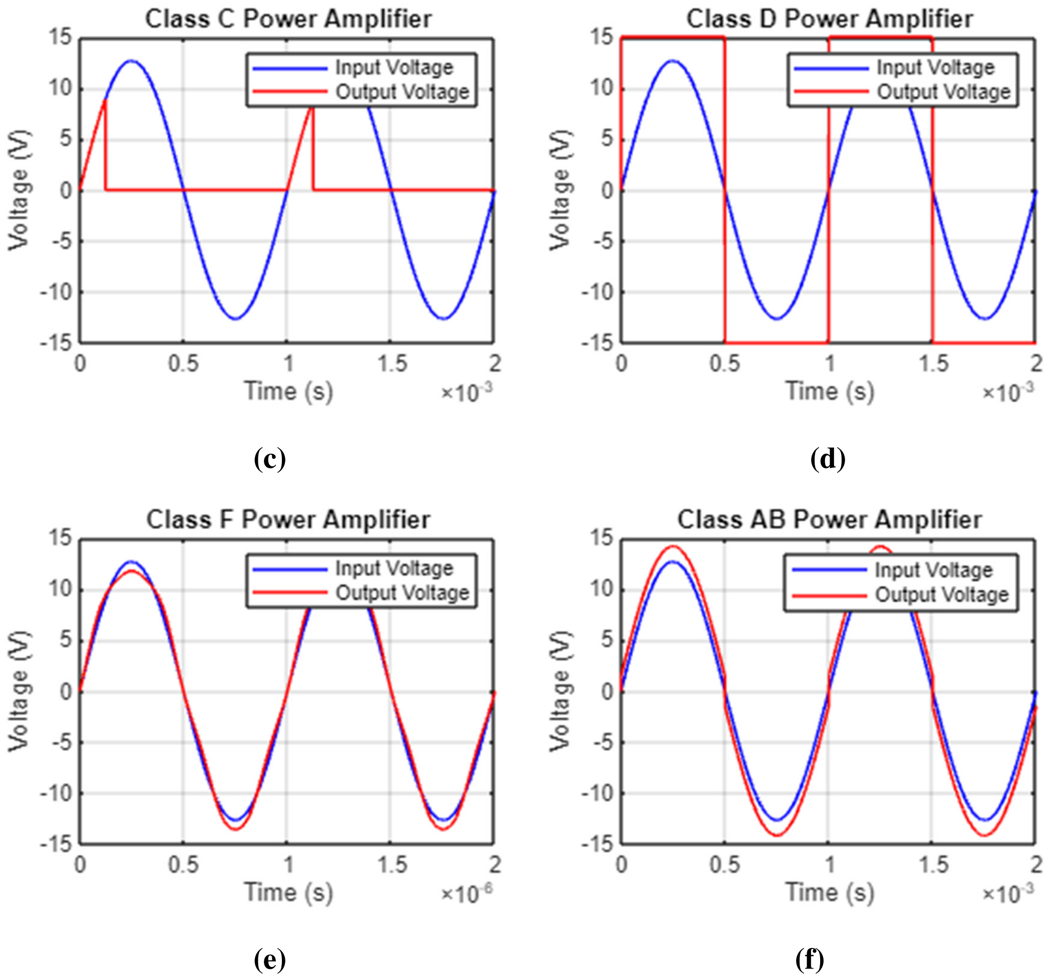


Figure 9. *Input and output voltages vary across different classes of power amplifiers.*

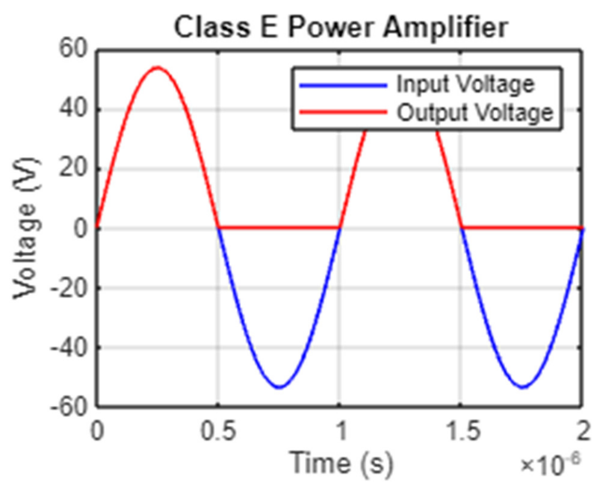


Figure 10. *Class E power amplifier input and output waveforms.*

Figure 10 shows the output voltage (red) and input voltage (blue) of a Class E power amplifier. Several factors must be considered when designing a power amplifier, including distortion, collector efficiency, and power dissipation capability, all of which affect the performance of the power amplifier.

10. Conclusion

This study provided a comprehensive analysis of common classes of power amplifiers, including classes A, B, C, D, E, AB, and F. The study focused on the key parameters affecting the performance of these amplifiers and presented experimental results using MATLAB to evaluate their performance. Insights from this study can help engineers, researchers, and students select and design power amplifiers for optimal performance in applications ranging from audio systems to wireless communications. The presented results provide a basis for research and development of high-efficiency power amplifier technology.

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