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-Theme-

Harmonic Distortion Analysis in Class D'Amplifiers

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Acknowledgements

Alhamdulillah...

Thank you to our parents...

Thank you to our siblings and family...

Thank you to our teachers...

Thank you to our friends...

Dedication

To my dearest parents and my entire family, whose unwavering dedication and endless support have been the cornerstone of my upbringing and education. To the teachers, mentors, and guides from my earliest days in primary school to the hallowed halls of university, who have imparted wisdom and shaped my intellect. To the brave children, resilient youth, devoted parents, and the noble martyrs of Gaza, whose sacrifices in the land of honor and resilience inspire us all. To the courageous souls who stand firm in the face of adversity, defending their homeland with valor and integrity. Your strength, perseverance, and unwavering commitment fuel my aspirations and dreams. This work is a tribute to your enduring spirit and boundless courage.

Youcef Essiddik Debbachi

Dedication

To my beloved parents and my entire family, whose unwavering dedication and endless support have been the cornerstone of my upbringing and education. To the teachers, mentors, and guides from my earliest days in primary school to the esteemed halls of university, who have imparted wisdom and shaped my intellect. To the brave children, resilient youth, devoted parents, and the noble martyrs of Gaza, whose sacrifices in the land of honor and resilience inspire us all. To the courageous souls who stand firm in the face of adversity, defending their homeland with valor and integrity. Your strength, perseverance, and unwavering commitment fuel my aspirations and dreams. This work is a tribute to your enduring spirit and boundless courage.

Khabbar Abdelaziz

Abstract

In this master's dissertation, we explore power amplifiers, delving into their diverse technologies and broad applications. Power amplifiers serve as crucial components in various electronic systems, ranging from audio amplification to wireless communication networks and beyond. We discuss the different classes of amplifiers and delve into their stages, efficiency, and performance metrics. Focusing particularly on the Class D amplifier, after introducing its characteristics, we conduct a detailed analysis study on THD+N. Finally, we conclude on the best feedback to use for optimal results.

key words: Power amplifier. Audio amplifier. Class D amplifier. THD+N. Feedback

Résumé

Dans cette dissertation de master, nous explorons les amplificateurs de puissance, en nous penchant sur leurs diverses technologies et leurs vastes applications. Les amplificateurs de puissance servent de composants cruciaux dans divers systèmes électroniques, allant de l'amplification audio aux réseaux de communication sans fil et au-delà. Nous discutons brièvement des différentes classes d'amplificateurs, en nous concentrant particulièrement sur les amplificateurs de classe D, en examinant leurs étages, leur efficacité et leurs métriques de performance. Après avoir introduit l'amplificateur de classe D et ses caractéristiques, nous avons mené une analyse de la THD+N et conclu avec des recommandations sur les meilleurs mécanismes de rétroaction pour obtenir des résultats optimaux.

Mots clés: Amplificateur de puissance. Amplificateur audio. Amplificateur de classe D. THD+N. Retour

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General Introduction

Behind all those booming speakers and clear headphones, there's a hidden hero: the power amplifier. It's like a supercharger for sound. It takes weak electrical signals from radios, microphones, or your phone and pumps them up strong enough to move the speakers and make those sounds come alive. Imagine a tiny voice trying to fill a whole stadium. Power amplifiers are like megaphones for electrical signals. They take weak signals from things like microphones or radios and make them strong enough to drive speakers, headphones, or antennas. There are different types of power amplifiers, like Class A, B, AB, and D. Each oneworks a little differently, affecting things like how much power they use and how clean the sound is. Some are better at one thing, while others are better at another. The various types of amplifiers, how they work, and the characteristics of each one will be discussed, in additionto the advantages and disadvantages of each one. Among this different types of amplifiers, special attention will be given to the Class D amplifiers, as it is classified better than the others. Class D amplifiers are a type of audio amplifier known for their efficiency and compact size. Unlike traditional amplifiers, which use analog methods to amplify signals, Class D amplifiers utilize a digital switching technique to amplify audio signals. This switching process allows Class D amplifiers to operate with very high efficiency, making them popular choices for applications where power consumption and heat dissipation are concerns, such as in portable audio devices, car audio systems, and home theater setups. Despite their efficiency, Class D amplifiers are capable of delivering high-quality sound, making them a versatile option for various audio applications. Class D amps are the champions of efficiency when it comes to boosting sound. They ditch the old way of amplifying and use a cool trick: pulse width modulation (PWM). Imagine a dimmer switch on fast forward - that's what PWM does. It turns electricity on and off really fast, matching the rhythm of the music. This saves tons of energy (like a battery saver for your music) and keeps things from overheating, making them perfect for speakers on the go, car stereos, and even home entertainment systems. There's another technique called delta-sigma modulation, which is like using a superprecise mold to shape the sound into a perfect stream. Both PWM and delta-sigma help Class D amps be super efficient, wasting less power and staying cool. This makes them ideal for situations where saving energy and keeping things compact is important. this dissertation is divided into three chapters Chapter 1: In this chapter, we talk about the different amplifiers Class A, B, AB, C, D, their definitions, how each one works, in addition to their advantages and disadvantages. Chapter 2: In this chapter, we go in depth specifically aboutthe Class D amplifier, its working principle, and its modulation technics and the different parts. Chapter 3: In this part, we conducted an analytical study of THD+n, compared the various results and analyses, and calculated the distortion rate to obtain the lowest noise rateand the highest quality rate[1].

Chapter 1: Power Amplifiers Overview

I.1 Introduction:

In this chapter, we will delve into the intricate world of telecommunications systems, witnessing their rapid evolution and the pivotal role played by power amplifiers (PAs) within them. As we explore further, we will encounter four distinct types of class amplifiers, each offering unique characteristics and efficiencies tailored to specific applications. From the venerable Class A amplifiers renowned for their pristine sound quality to the highly efficient Class D amplifiers favored for their compact size and low heat dissipation, we will unravel the intricacies of each amplifier class. Moreover, we will delve into the critical role of power amplifiers in telecommunications, where they serve as the backbone of signal transmission, amplifying data before it embarks on its journey through antennas. Through this exploration, we will gain insights into the challenges and innovations shaping modern telecommunications networks, as well as the pivotal role of power amplifiers in meeting the ever-growing demands for faster data rates and enhanced connectivity.

I.2 Power Amplifier:

A power amplifier is designed to deliver significant power to a load, necessitating its capability to handle and dissipate substantial amounts of power. When operated at high current and voltage levels, it generates heat, which must be efficiently released into the surroundings to prevent overheating. Typically, power amplifiers incorporate bulky components with large surface areas to facilitate heat transfer. Among these components is the power transistor, a discrete device enclosed in a metal case with a substantial surface area [2].

I.3 Audio amplifier:

Audio amplifiers are electronic circuits designed to increase the power of low-level audio signals. This allows them to drive loudspeakers which require much higher power to produce sound [3].

- **Amplifier Efficiency:** It is defined as the ratio of output AC power to the inputDC power.

$$\boldsymbol{\eta = \frac{P_{ac}}{P_{dc}} \times 100 = \frac{P_{dc}}{P_{ac}}} \qquad \textbf{1.1}$$

- **Distortion:** The change in output wave shape from the input wave shape of an amplifieris known as distortion. The distortion can be reduced by using negative feedback in the amplifier [4].

I.3.2 Classes of power amplifier:

Power Amplifiers are classified into different categories depending on how efficiently they operate and how they handle the input signal. in Figure 1.1 break down of the most common classes:

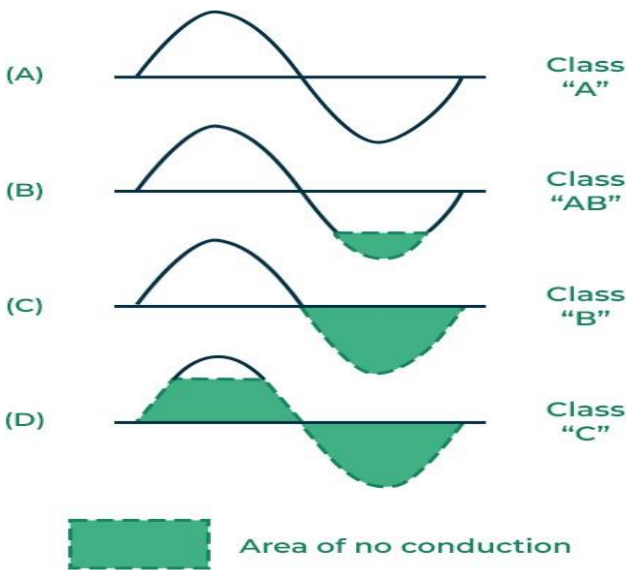

Figure 1.1: Graphs of Classes of Power Amplifier

a) Class A power amplifier:

Class A amplifiers as presented in Figure 1.2 function by ensuring that the output transistors conduct throughout the entirety of the input signal cycle. This design minimizes distortion but compromises efficiency due to continuous transistor conduction, which generates considerable heat [5].

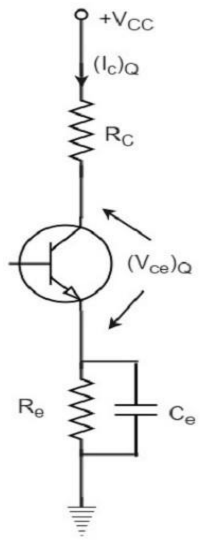

Figure 1.2: class A power amplifier

b) Class A Amplifier Efficiency:

The efficiency is defined to be average signal power delicered to load average power drawn from DC source.

- **Advantage of class A amplifier:**

Class A amplifiers exhibit exceptional linearity, ensuring uniform and stable output over various frequencies and amplitude levels. This consistent output quality is crucial for applications that demand high-fidelity sound reproduction.

- **disadvantage:**

Class A amplifiers have lower power efficiency than Class C, B, and AB amplifiers, resulting in substantial power dissipation in the power transistors.

c) class A amplifier working:

The type of amplifier we choose determines its power consumption and how it alters the signal. In the diagram, the first wave represents the input signal that drives the transistor, while the second wave illustrates the resulting output signal [6].

In Figure 1.3, the horizontal line indicates the portion of the signal utilized by the transistor. In this case, the transistor utilizes the entire signal, meaning the amplifier operates continuously, resulting in lower efficiency, typically around 25 to 30 percent. However, it excels at amplifying the signal, which we refer to as gain. This type of amplifier maintains the fidelity of the original signal while increasing its magnitude. It's crucial to avoid driving the transistor into saturation or cut-off by adjusting the input signal appropriately. Otherwise, the output waveform may exhibit clipped peaks [7].

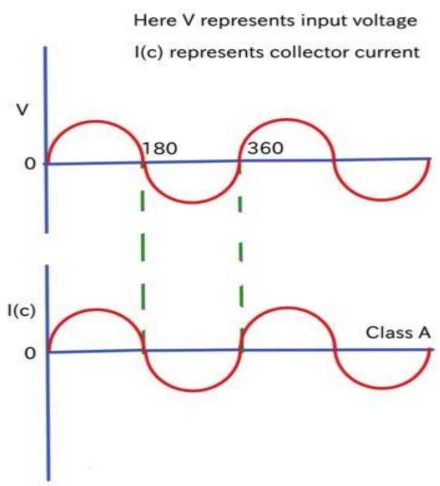

Figure 1.3: class A power amplifier

- **Applications of Class A Amplifier in Real World:**

– Voltage amplifier.

– Current amplifier.

– Power amplifier.

d) Class B power amplifier:

A Class B amplifier, as presented in Figure 1.4, is characterized by the collector current (Ic) flowing only during the positive half cycle of the input signal. This type of power amplifier utilizes two complementary transistors (one PNP and one NPN) to handle each half cycle of the input signal. Consequently, each transistor conducts for 180 degrees of the signal cycle. When one of the complementary transistors is positively biased to conduct during the positive signal phase, the other transistor is turned off to ensure efficient operation [8].

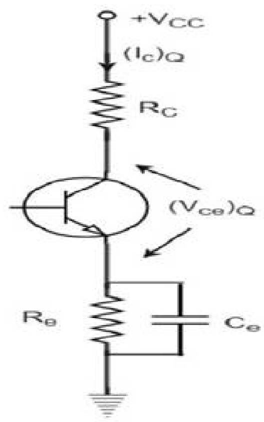

Figure 1.4: Class B power amplifier

e) Class B Amplifier Efficiency:

the efficiency of a class B amplifier can be determined using the following formula:

$$\textbf{Efficiency}\ \% = \frac{\boldsymbol{Po_{ac}}}{\mathbf{Pi(dc)}}\ \mathbf{100\%} \qquad \mathbf{1.2}$$

$$= \frac{\mathbf{Pi}}{\mathbf{4}} * \frac{\mathbf{VL(p)}}{\mathbf{VCC}}\ \mathbf{100\%}$$

f) Class B amplifier working:

During the positive half cycle of the input signal, the base-emitter (B-E) junction of the transistorbecomes forward-biased, allowing base current to flow when a sinusoidal input signal is applied to the transistor’s base. By employing two transistors in a push-pull arrangement, the amplifier can generate the full cycle of the output signal by alternating between the two transistors during each half cycle of the input signal, effectively eliminating distortion. Each transistor operates for 180 degrees of the signal cycle. This type of amplifier is commonly referred to as a push-pull Class B power amplifier [9].

- **Advantages of class B amplifier:**

One significant advantage of Class B amplifiers over their Class A cousin amplifier is thatno current passes through the transistors when they are in their quiescent state, meaning when there's no input signal. As a result, no power is wasted in the output transistorsor transformer in the absence of a signal. This stands in contrast to Class A amplifiers,which necessitate substantial base bias and consequently dissipate considerable heat even without an input signal [10].

- **Disadvantages of class B amplifier:**

Class B amplifiers come with several drawbacks:

- Crossover distortion may arise, affecting signal fidelity.
- Distortion levels tend to be higher compared to Class A amplifiers.
- Maintaining a stable power supply is crucial due to fluctuating current demands.
- Obtaining complementary transistors with matching characteristics can be challenging.
- Both positive and negative voltage supplies are necessary.
- Self-biasing is unnecessary, adding complexity.
- Connecting transformers to the circuit can increase size and cost.
- Transformer coupling may introduce vibrations in the output, potentially impacting frequency response [11].

g) Class AB Power Amplifier:

As the name states, AB amplifiers as presented in Figure 1.5 are a combination of class A and class B amplifier. This one solves the reduced efficiency issue in the class A amplifier, and also solves the crossover distortion issue presents in class B amplifier.

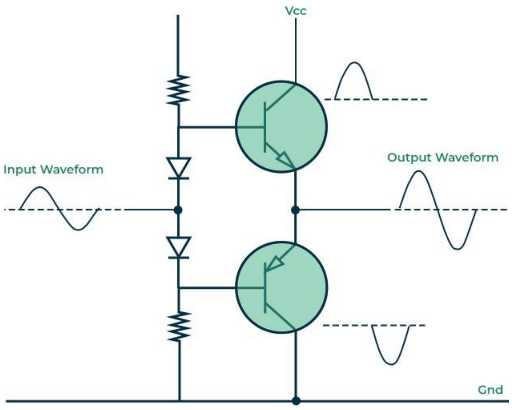

Figure 1.5: Class AB power amplifier

h) class AB amplifier working:

The class AB Amplifier combines features of both Class A and Class B amplifiers. Atlow power outputs, both output devices conduct, operating the amplifier akin to a Class A amplifier. However, by increasing bias, the amplifier transitions into Class B

operation. This allows it to share characteristics of both classes, forming the Class AB mode. Achieving this configuration involves pre-biasing the two transistors in the amplifier's out- put stage. In Class AB mode, each output transistor conducts between 180 and 360 of the time, depending on the load current output and pre-biasing setup. This arrangementenables the amplifier's output stage to function effectively as a Class AB amplifier [12].

i) Class AB Amplifier Efficiency:

Class AB amplifiers give higher efficiency compared to both Class B and Class A amplifiers. The biasing in Class AB amplifiers effectively eliminates crossover distortion. Efficiency defined by the ratio of AC output power to DC input power, It is denoted by η [13].

$$\boldsymbol{\eta = {}^{Pout}/_{Pdc}} \qquad \textbf{1.3}$$

- **Advantages of a Class AB amplifier:**

- Elimination of crossover distortion stands as its primary advantage.
- Offers greater efficiency and signal amplification compared to Class A amplifiers.
- Maintains linearity, with the output signal's amplitude and phase matching the input.
- Favored for applications like radios, audio systems, and TV receivers.
- Delivers high efficiency alongside a robust high-frequency response.
- Minimizes harmonic distortion, enhancing signal fidelity[14].

- **Disadvantages of a Class AB amplifier:**

- Class AB amplifiers typically exhibit lower efficiency compared to Class B amplifiers.
- The circuit construction tends to be complex.
- Higher cost is associated with the components and assembly.
- Improper biasing can lead to spikes in the output signal, causing crossover
- distortion[15].

j) Class C Power Amplifier:

Class C power amplifiers as presented in Figure 1.6 operate with transistor conduction for lessthan 180, typically ranging from 80 to 120, corresponding to one-half cycle of the input signal.This reduced conduction angle significantly enhances efficiency but introduces considerable distortion.

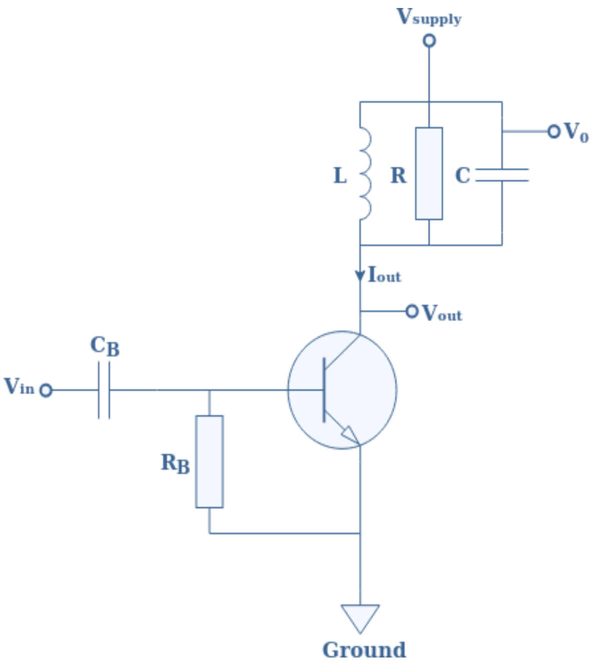

Figure 1.6: Basic structure of a class C amplifier

k) Class C Amplifier Efficiency:

Class C amplifiers are highly efficient, typically achieving efficiencies ranging from 70% to 80%. They achieve this efficiency by operating with a conduction angle of less than 180 degrees. This makes them ideal for applications such as RF transmission and pulse modulation, where linearity is less critical and high-power output with minimal heat generation is desired. However, a trade-off for this efficiency is significant harmonic distortion, which limits their suitability to non-audio and non-linear applications [16].

- **The advantages of class c amplifier:**

– Typical Efficiency: Class C amplifiers typically achieve efficiencies between 70% and 80%, significantly higher than Class A, B, or AB amplifiers.

– Reduced Power Loss: The design minimizes the time the active devicespends in conduction, reducing power loss and heat generation.

– The high efficiency leads to lower energy consumption and reduced operational costs over time.

- **The Disadvantages of class c amplifier:**

– Non-Linear Operation: The amplifier conducts for less than 180 degrees of the input signal cycle, leading to a highly distorted output that needs extensive filtering.

– Significant Harmonic Distortion: Class C amplifiers introduce substantial harmonic distortion, making them unsuitable for applications requiring high-fidelity audio or linear signal amplification.

l) Class D Power Amplifier:

Class D amplifiers, as presented in Figure 1.7, are a type of amplifier that rapidly switches between fully on and fully off states. This switching action minimizes power losses in the output devices, resulting in very high efficiency, often reaching 90-95%. These amplifiers operate by using the audio signal to modulate a special type of signal known as Pulse Width Modulation (PWM). The PWM signal then drives the output devices, which reproduce the audio signal. Finally, a low pass filter is employed to remove the high-frequency PWM components, ensuring that only the original audio signal remains [17].

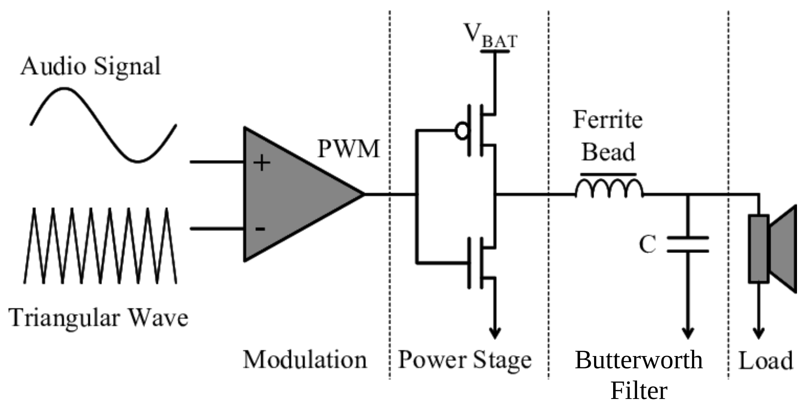

Figure 1.7: Basic class-D amplifier.

- **Advantages of a Class D amplifier:**

– Energy Efficiency: Class D amplifiers are highly energy efficient, converting the audio signal into amplified output with minimal heat dissipation. Typical Class D amplifiers achieve efficiency rates between 80-90%, with advanced models like ICE power's reaching up to an impressive 97%. In contrast, linear amplifiers, such as Class AB, typically operate at 40-60% efficiency, while Class A amplifiers often fall below 10%.

– Compact Size: Class D amplifiers are smaller and lighter than linear ones. This smaller size makes them great for places where there isn't much space.

– Cool Operation: Unlike Linear amplifiers, which can get quite hot, Class D amplifiers stay cool during operation. This cool operation brings several benefits, such as a longer lifespan and less need for big, heavy heatsinks and fans.

– Transparent Audio: Class D amplifiers prioritize audio quality, delivering clear sound with minimal noise and distortion for an optimal listening experience. Even if youprefer the sound of a linear amplifier, you can adjust your Class D amplifier to match it.

These attributes make Class D amplifiers perfect for applications needing highpower in a small size, with low energy usage and minimal heat generation

I.3.3 Applications of power amplifiers:

a) Audio systems:

Driving speakers in home theaters and concert venues.

b) Wireless Communications:

Power amplifiers are useful in sending radio signals from cell towers and satellites. They make it possible to send signals at higher power levels, which helps increase data transfer speeds and how well the systems work.

c) Radar Systems:

in the radar systems it amplifies radar signals for accurate object detection.

- **Industrial:**

Power amplifiers find applications in servo motors and DC motors. Switching-type poweramplifiers are commonly utilized for controlling many industrial actuator systems.

They play a crucial role in managing motors and actuators in various manufacturing processes.

- **Medical Equipment:**

  Powering ultrasound and MRI systems. Summary of amplifier classes in Table 1.1

Table 1.1: Comparison of Different Classes of Power Amplifiers

Power Amplifier Class	Efficiency	Linearity	Distortion	Applications
Class A	Low	Excellent	Minimal	High-fidelity audio
Class B	Moderate	Good	Moderate to High	Motor control, power inverters
Class AB	Moderate	Good	Moderate	Audio amplification, car audio
Class C	High	pour	High	RF signal amplification, broadcasting
Class D	High	Good	Low	Portable audio devices , power-efficient apps

I.4 Conclusion:

In this chapter, we explored the realm of Power Amplifiers, investigating their categorization into distinct groups and delving into the various types within each class. These amplifiersplay a pivotal role in electronics by bolstering signal strength, rendering them indispensable across a broad spectrum of applications spanning from sound systems to radio transmitters. Their significance in modern technology cannot be overstated, as they serve as the backbone ofnumerous electronic devices, facilitating clearer communication, enhanced audio quality, and efficient signal transmission. Through understanding their classifications, characteristics, and widespread utility, one gains insight into the fundamental workings of electronic systems and their pervasive impact on contemporary society.

Chapter 02 : Class D Power Amplifier

II.1 Introduction:

Class D amplifiers indeed mark a significant evolution in audio amplification technology. They are distinct from their predecessors—Class A, B, AB, and C amplifiers—primarily due to their high efficiency and low heat production. Unlike traditional linear amplifiers (Class A, B, and AB) that operate in continuous conduction mode, Class D amplifiers function by switching transistors on and off at a high frequency, which significantly reduces power loss. The Total Harmonic Distortion plus Noise (THD+N) is a critical measure of fidelity in amplifiers. Class A, B, and AB amplifiers, while offering simpler designs and excellent audio quality, often suffer from higher power dissipation due to their continuous operation and the resulting heat and very poor efficiency. Class B and AB amplifiers, in particular, introduce crossover distortion,a form of THD+N, when transitioning between the positive and negative halves of the audio signal. Class D amplifiers, on the other hand, have historically been challenged by THD+N due to factors such as the inherent switching noise of their output transistors and electromagnetic interference (EMI). However, modern Class D amplifiers have significantly improved in this regard. Advances in modulation techniques, such as Pulse Width Modulation (PWM), and feedback systems have mitigated many of the THD+N issues previously associated with ClassD designs These improvements have made Class D amplifiers competitive with linear amplifiers in terms of audio quality, while also maintaining their inherent efficiency advantage.

II.2 Definition and Explanation:

A Class D amplifier, also known as a switching amplifier, is a type of audio amplifier that utilizes digital switching methods to boost signals. Unlike traditional analog amplifiers that amplify continuously, Class D amplifiers enhance sound by rapidly switching the signal on and off. This efficient technique allows for a powerful output while minimizing energy loss and heatproduction [18].

II.2.1 Historical Context of Class D Amplifiers:

The concept of the Class D amplifier was first introduced by British scientist Alec Reeves in the 1950s and was officially named in 1955. The early commercial embodiment of this technologywas the X-10, a kit module released by Sinclair Radionics in 1964. However, with an outputof only 2.5 watts and the limitations of germanium-based bipolar junction transistors of the time, it wasn't a practical solution for widespread use [19]. The real breakthrough for Class D amplifiers came with the advent of silicon-based MOSFET (metal–oxide–semiconductor field- effect transistor) technology. In 1978, Sony introduced the TA-N88, the first-Class D amplifierto utilize power MOSFETs and a switched-mode power supply. This period also saw rapid developments in MOSFET technology, particularly between 1979 and 1985. By the mid-1980s,the availability of low-cost, fast-switching MOSFETs led to the commercial success of ClassD amplifiers [20]. In 1996, the first-Class D amplifier based integrated circuit was released by Tripath, which then saw widespread use. Today, Class D amplifiers are highly regarded for their efficiency, often exceeding 90%, due to their transistors operating in a fully on or off state, which significantly reduces power dissipation. They are now a staple in various audio applications, from consumer electronics to professional sound systems.

II.2.2 The Basics of Class D Amplifiers:

In modern Class D amplifiers presented in Figure 2.1, various modulator topologies are employed. However, the fundamental topology involves pulse-width modulation (PWM) usinga triangle-wave (or sawtooth) oscillator. Figure 2.1 depicts a simplified block diagram of a PWM-based, half-bridge Class D amplifier. It comprises a pulse-width modulator, two output MOSFETs, and an external low pass filter (LF and CF) to recover the amplified audio signal.The p-channel and n-channel MOSFETs function as current-steering switches, alternatingly connecting the output node to VDD and ground. Consequently, the output of a Class D amplifier is a high-frequency square wave, with a switching frequency (fSW) typically ranging from 250kHz to 1.5MHz. PWM occurs by comparing the input audio signal to an internally generated triangle-wave (or sawtooth) oscillator. This modulation technique, often termed “natural sampling,” utilizes the triangle-wave oscillator as the sampling clock. The duty cycle of the resulting square wave corresponds to the input signal level. When no input signal is present, the output waveform’s duty cycle remains at 50%. Figure 2.1 illustrates the resulting PWM output waveform, which varies based on the input-signal level [21]

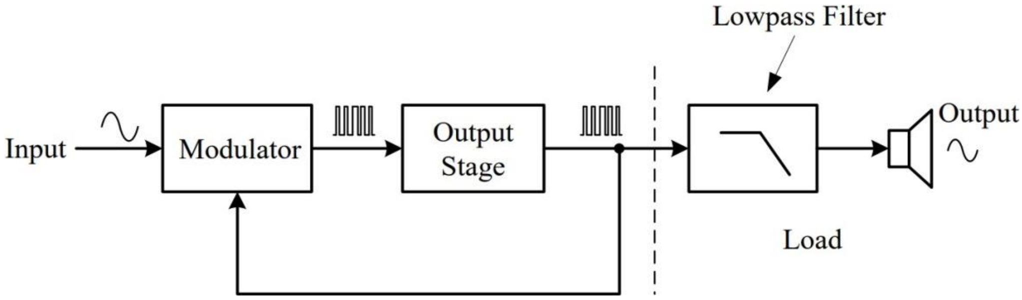

Figure 2.1: Block diagram class D amplifier

II.3 Class D amplifier modulation technique:

Class D amplifiers use a variety of modulation techniques to enhance performance. The primary method is Pulse Width Modulation (Modulation de largeur d’impulsion or PWM), where audiosignals are converted into pulses of varying widths corresponding to signal amplitude, ensuringhigh efficiency through minimal energy loss. Additionally, Sigma-Delta Modulation and Bang- Bang Control further reduce Total Harmonic Distortion plus Noise (THD+N), improving audio quality. Auto-oscillating techniques are also used to achieve stable operation and precise control of the output signal, enhancing overall performance and fidelity [22].

II.3.1 Pulse Width Modulation:

Class D amplifiers primarily use Pulse Width Modulation (Modulation de largeur d’impulsionor PWM) to boost performance. In PWM, the audio signal is transformed into pulses of

varying widths reflecting the signal’s amplitude. This method optimizes efficiency by ensuring the output transistors switch between fully on and off states, thus minimizing energy loss. BesidesPWM, techniques like Sigma-Delta Modulation, Bang-Bang Control, and auto-oscillating methods are employed to further reduce Total Harmonic Distortion plus Noise (THD+N), thereby enhancing audio fidelity and operational stability. Figure 2.3 presents a schematic of an open- loop PWM Class D Amplifier As presented in Figure 2.1. It features a PWM modulator with acarrier generator and a comparator, an output stage, and a load coupled with a low pass filter.The modulator generates a PWM signal by contrasting the analog input with a carrier wave,often triangular or sawtooth. This signal is then boosted by the output stage to power the load [23].

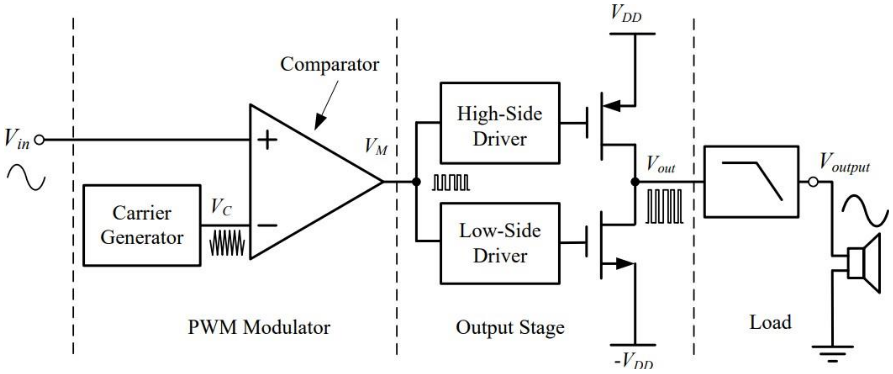

Figure 2.2: Schematic of an open-loop PWM Class D amplifier

II.3.2 Sigma-Delta Modulation:

Sigma-Delta Modulation in Class D amplifiers as presented in Figure 2.3 significantly enhances audio performance by transforming the input signal into a high-frequency pulse train with minimal quantization noise. This technique involves oversampling the input and applying noise shaping to shift quantization noise to higher, more easily filtered frequencies, thereby reducingTotal Harmonic Distortion plus Noise (THD+N). Consequently, Sigma-Delta Modulation improves the audio fidelity and resolution, making Class D amplifiers highly suitable for high-end audio applications where sound quality is paramount [24].

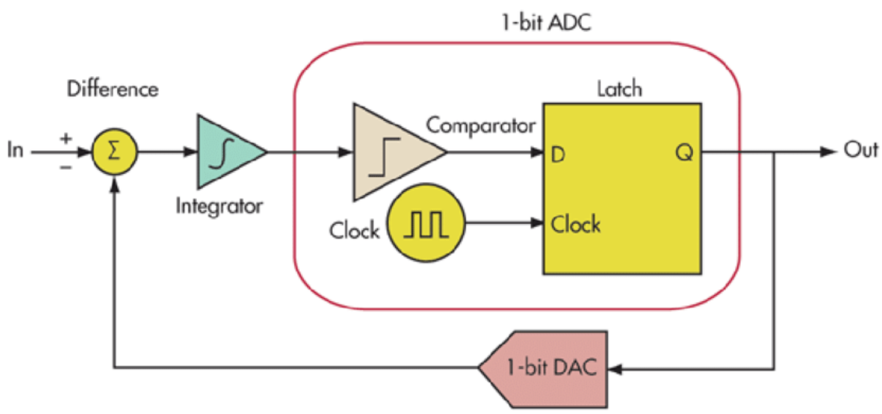

Figure 2.3: Delta sigma modulator scheme

II.3.3 Synchronous Sigma-Delta CDAs:

Synchronous Sigma-Delta Class D Amplifiers as presented in Figure 2.4 (CDAs) are a sophisticated type of digital amplifier that combine the principles of sigma-delta modulation with Class D amplification techniques. These amplifiers are designed to convert analog signals into high-frequency digital pulses, which are then amplified and filtered to produce high-fidelity audio output. The synchronous aspect refers to the synchronization of the modulator’s clock with the system clock, which can help to reduce jitter and improve the overall stability of the conversion process. This synchronization is crucial in applications where timing precision is essential, such as in audio and instrumentation systems [25].

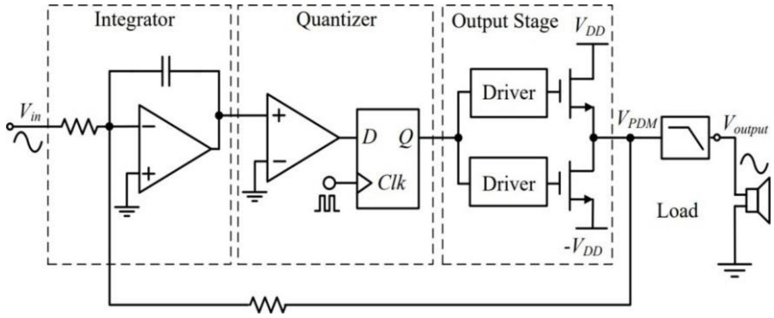

Figure 2.4: Schematic of a first-order synchronous Sigma-Delta CDA

II.3.4 Asynchronous Sigma-Delta CDAs:

Figure 2-5 illustrates the design of an asynchronous Sigma-Delta Continuous-Time Digital-to- Analog Converter (Sigma-Delta CDA), which bears resemblance to the synchronous version. The distinguishing feature lies in the quantizer’s operation, which is governed by the activity ofa hysteresis comparator rather than an external timing signal. The merit of this asynchronous approach is the theoretical elimination of quantization noise1, attributed to the sampling beingregulated by a continuous-time comparator, thus enhancing the signal fidelity.

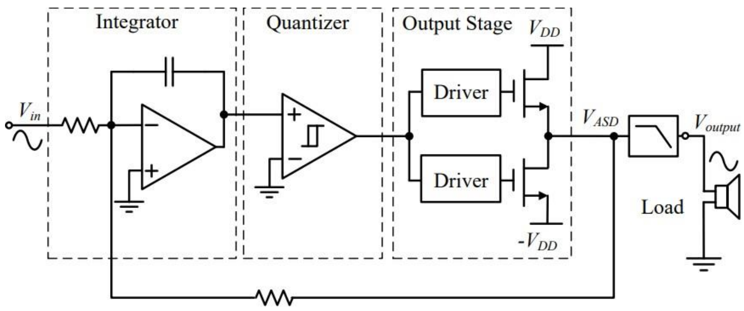

Figure 2.5: Schematic of a first-order asynchronous Sigma-Delta CDA

II.3.5 Bang-bang control Class D Amplifiers:

The bang-bang Class D amplifier (ACD), shown in Figure 2.6, is less popular compared to PWM and sigma-Delta modulations due to their previously offered advantages. However, the bang-bang ACD has the simplest hardware and the highest energy efficiency. It only dissipatespower at rest through the hysteresis comparator. Unlike PWM and sigma-Delta ACDs, which use power-consuming integrators, the bang-bang ACD is more energy-efficient. Additionally, its lower switching frequency results in reduced switching power losses [25].

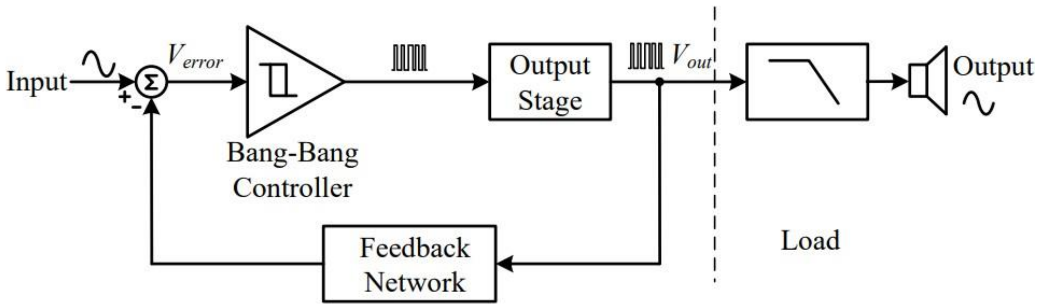

Figure 2.6: Block diagram of a Bang-bang CDA

II.3.6 self-oscillation:

In the domain of Class D amplifiers, the concept of self-oscillation plays a crucial role, shaping both their performance and design considerations. Auto-oscillation shown in Figure 2.7 denotes the inherent capability of the amplifier to produce its oscillating signal without external input. In Class D amplifiers, which function by swiftly switching output transistors between fully on and off states, auto-oscillation may arise from factors like parasitic capacitances, inductances, and stray impedances within the circuit. While this phenomenon can potentially lead to in- stability and distortion, it also offers opportunities for improving efficiency and simplifying amplifier designs. Engineers frequently employ advanced feedback mechanisms and compensation techniques to manage auto-oscillation, ensuring stable operation and optimal performance. Through meticulous balancing of efficiency, distortion, and stability trade-offs, Class D amplifiers leverage auto-oscillation to achieve high-fidelity audio reproduction with minimal power consumption, establishing them as a favored choice in modern audio systems [1].

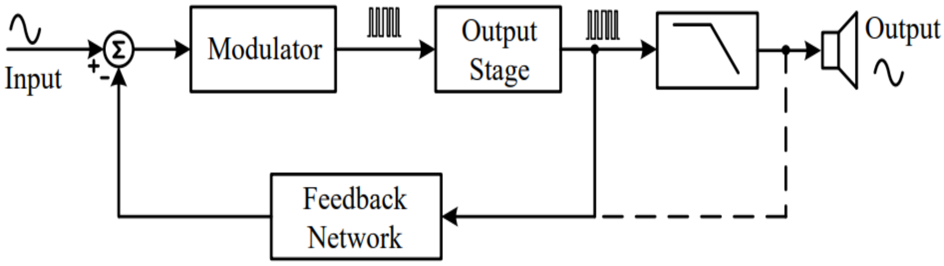

Figure 2.7: Self-oscillating Class D amplifiers block diagram

II.4 Main class D audio amplifier stages:

II.4.1 Output stage:

The output stage shown in Figure 2.8 is a vital element of any Class D amplifier, as it not only takes up a substantial portion of the silicon chip but also uses a major share of the overall power. For example, a certain Class D amplifier driving an 8 w speaker can have the output stage accounting for more than 70% of the active area and over 90% of the power consumption. Although its schematic may seem simple, especially when compared to modulators, the output stage's large size and power handling significantly influence the amplifier's performance metrics. Critical components like the dead-time circuit play a significant role in ensuring the amplifier's reliability and sound quality [26].

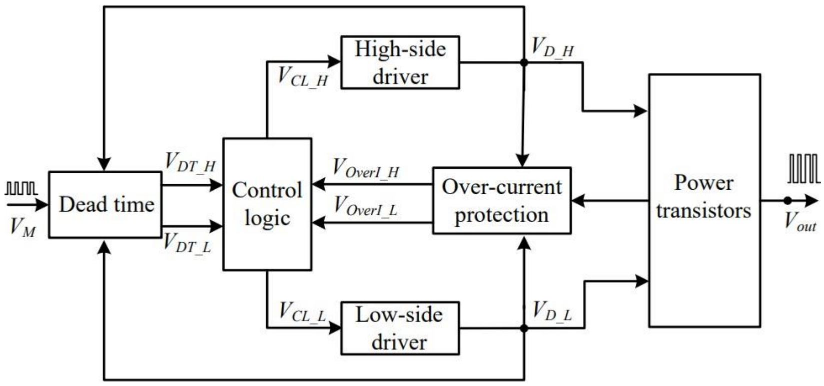

Figure 2.8: Block diagram of a Class D output stage

II.4.2 Filtering:

The filtering stage in a Class D amplifier is crucial for its operation. It typically involves an LC low-pass filter, which serves to extract the audio signal from the high-frequency pulse-width modulated (PWM) output. This stage is essential because, without it, the loudspeakers would be subjected to the full range of high-frequency switching noise, which is not only undesirable for audio quality but can also be harmful to the speakers [27].

II.4.3 LC low-pass filter:

Filters, particularly in the context of Class D amplifiers, are designed to perform a critical function: they filter out the high-frequency components from the amplifier's output while allowing the desired audio signal to pass through

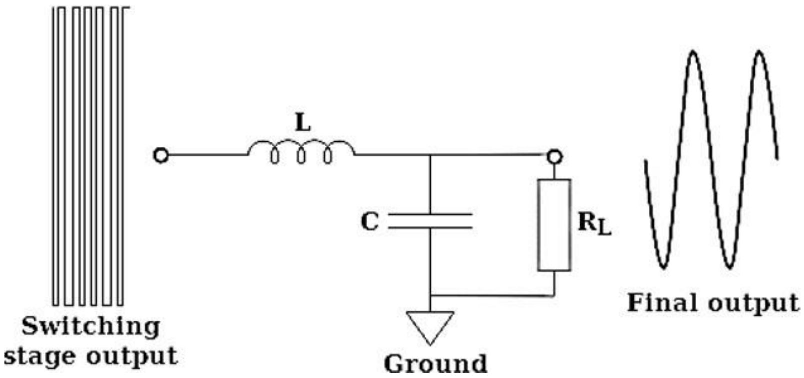

Figure 2.9: Low-pass LC filter

The bandwidth of this filter is characterized by its cutoff frequency Fc at -3 dB that satisfiesthe:

$$FC = \frac{1}{2\pi\sqrt{LC}} \quad 2.1$$

II.4.4 Comparator:

a) Definition:

A comparator is a device or instrument that compares two quantities, signals, or values and outputs a result indicating which is larger or if they are equal. Comparators are widely used in electronics, engineering, and various scientific fields to facilitate decision-making processes based on comparisons of input variables [28].

b) Comparator in class D amplifier:

In a Class D amplifier, the comparator shown in Figure 2.10 plays a vital role in the modulation process. This type of amplifier converts the input analog signal into a high-frequency pulse-width modulated (PWM) signal. The PWM signal is then used to control power transistors, which rapidly switch on and off to produce a high-power PWM output signal. This output is subsequently filtered through a low-pass filter to retrieve the amplified analog audio signal. The comparator functions by comparing the input analog signal with a high-frequency triangular or sawtooth waveform, known as the carrier signal. It generates a PWM signal where the pulse width is directly proportional to the input signal's amplitude. When the input signal surpasses the carrier signal, the comparator outputs a high signal; when the input signal is lower, the output is low. This process creates a PWM signal that accurately mirrors the original analog input but in a digital format, making it suitable for amplification by the switching transistors [29].

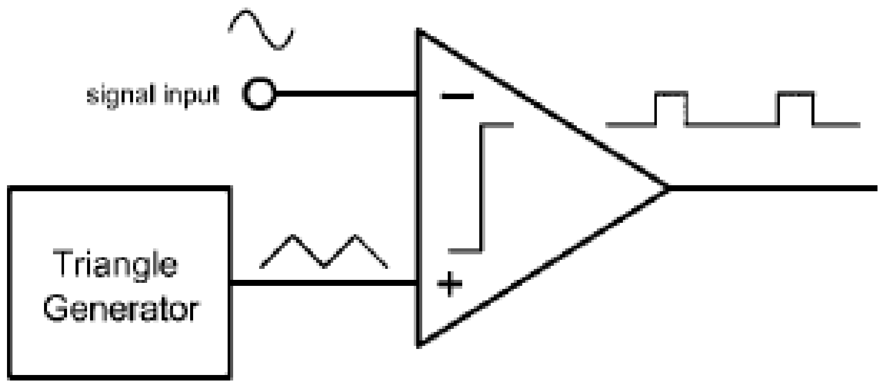

Figure 2.10: comparator in class D

II.4.5 Integrator:

The op-amp integrator shown in Figure 2.11 circuit is a fundamental electronic component that performs real-time integration, outputting a voltage that represents the time integral ofthe input voltage. It's constructed with an operational amplifier, a resistor, and a capacitor.The op-amp operates in inverting mode, with the resistor replaced by a capacitor to form the feedback loop. This configuration allows the capacitor to charge in response to the input.

Voltage, creating a ramp-like output that varies proportionally with the integral of the input signal. The circuit's behavior is governed by the RC time constant, which dictates the rate at which the capacitor charges. The op-amp integrator is essential in various applications that require the integration of an electrical signal, such as in analog computers or signal processing. It's valued for its ability to provide a continuous and precise representation of the integrated input signal [30].

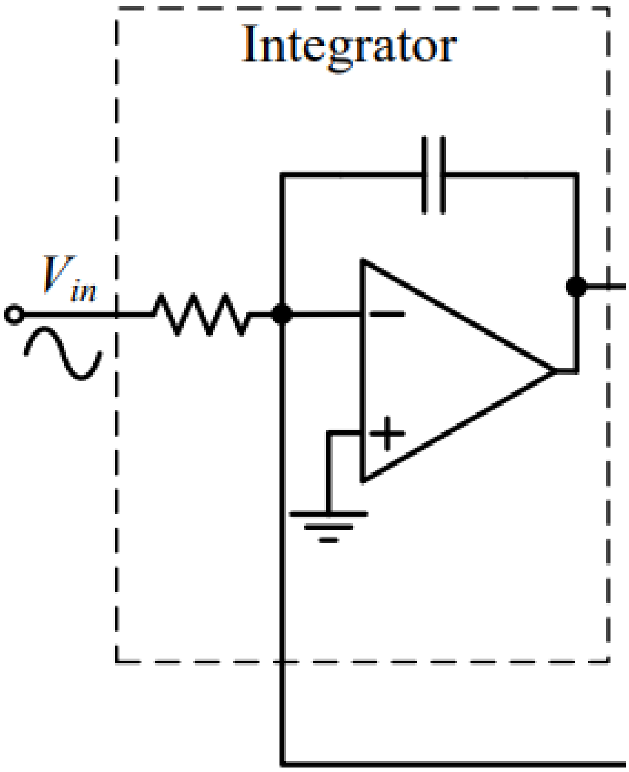

Figure 2.11: circuit diagram of an op-amp based integrator

II.5 Feedback:

A feedback amplifier is an electronic circuit designed to improve its performance by routing a portion of its output back to its input. This process involves sampling the output signal, comparing it with the initial input, and adjusting the amplification accordingly. We will next explore the block diagram and the operational principles of a feedback amplifier [31].

II.5.1 Types of feedback:

a) Positive Feedback:

In Class D amplifiers, positive feedback shown in Figure 2.12 is a configuration wherea part of the output signal is routed back to the input with identical polarity. Thistype of feedback can amplify the gain, but it must be managed with precision to preventinstability. Due to the inherent risk of causing oscillations and distortion, positive feed- back is seldom utilized in Class D amplifiers, as maintaining the integrity of the signal is paramount in these systems.

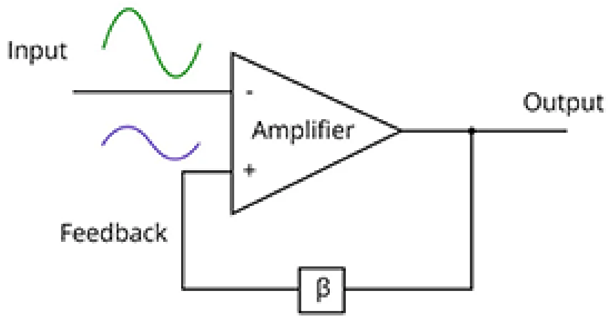

Figure 2.12: positive feedback

b) Negative Feedback:

Negative feedback shown in Figure 2.13 in Class D amplifiers is a technique where apart of the output signal is inverted and reintroduced into the input. This method yields several advantages: it significantly reduces distortion by correcting nonlinearities, enhances stability by preventing oscillations, and improves power-supply rejection (PSR)by diminishing noise from the power supply. Such feedback is essential for the high- performance operation of Class D amplifiers.

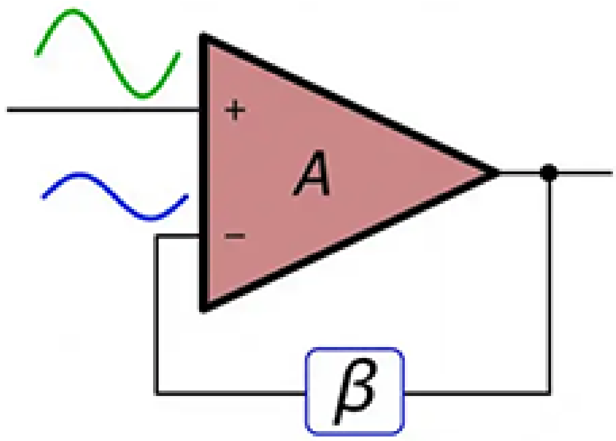

Figure 2.13: Negative feedback

II.5.2 Key performances:

- **The Efficiency:**

Class D amplifiers are renowned for their high efficiency shown in Figure 2.14, which is a standout feature in their design. They can achieve peak efficiencies of up to 90% or more,a significant improvement over the 30% peak efficiency of Class A amplifiers and about 60% for Class AB amplifiers. This efficiency is due to the fact that Class D amplifiers use their transistors as switches, steering current through the load with minimal energy loss. The power that is lost is primarily due to the on-resistance of the output transistors, switching losses, andquiescent current overhead. As a result, most of the power in a Class D amplifier is used for amplification rather than being dissipated as heat, which is why they are particularly suited for portable and compact high-power applications [32].

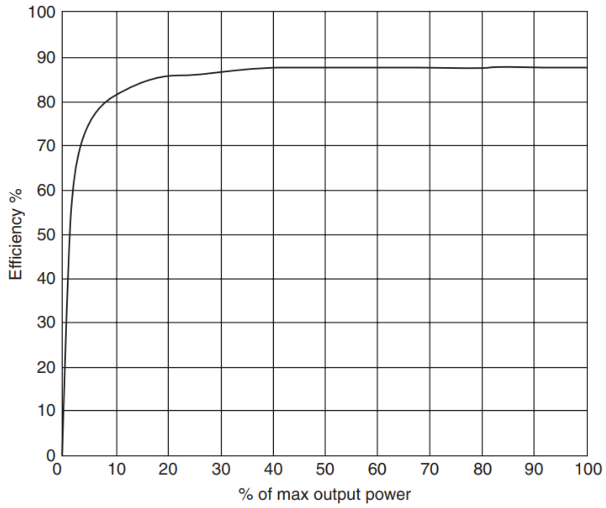

Figure 2.14: A typical efficiency curve for a Class-D amplifier

II.6 Total Harmonic Distortion Plus Noise (THD+N):

is a measure used to assess the fidelity of an audio device, particularly amplifiers like Class D amplifiers. It quantifies the unwanted harmonics and noise present in the output signal relativeto the energy of the input signal. The THD+N value is expressed as a percentage, indicating the proportion of these distortions and noise to the original signal.

The equation for THD+N is typically represented as:

$$\boldsymbol{THD + N = \frac{\sum_{n-2}^{\infty} harmonics + noise}{fundamental} * 100\%} \qquad \mathbf{2.2}$$

The impact of THD+N on sound quality is significant. When the THD+N percentage islow, it reflects a more faithful and clean audio signal transmission, with minimal distortion andnoise. Conversely, a high THD+N percentage can lead to noticeable flaws in the sound, which can detract from the overall auditory experience. For Class D amplifiers, it's crucial to keep THD+N at minimal levels to ensure the output is of high-fidelity [32].

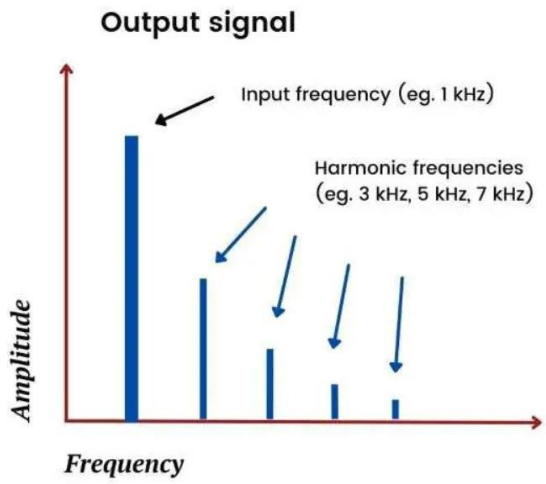

Figure 2.15: Output signal of an audio device showing harmonic distortion

II.6.1 How (THD+N) is measured in audio systems:

Two commonly used methods for measuring harmonic distortion in audio systems are Total

Harmonic Distortion (THD) and Total Harmonic Distortion plus Noise (THD+N). Although these metrics are conceptually similar, THD+N is generally easier to measure than THD. THD+Nis also more beneficial for audio applications because it accounts for additional noise sources beyond harmonic distortion, such as hum, interference, and white noise. Consequently, audiodevice specifications, including those for audio interfaces and amplifiers, often cite THD+N rather than THD[33].

II.6.2 The acceptable range of THD+N in audio interfaces:

The specification of Total Harmonic Distortion Plus Noise (THD+N) in audio interfaces is essential, as it measures the proportion of undesired harmonic and noise interference relative to the intended audio signal. In the realm of high-quality sound reproduction, a THD+N value that is below 0.01% is often sought after, as it reflects a negligible modification of the original audio. Such a low THD+N value is considered within the acceptable range for premium audio interfaces, guaranteeing that both distortion and noise are kept at levels that are imperceptible, thereby preserving the integrity of the audio experience [34].

II.7 Conclusion:

Class D amplifiers stand as a pinnacle of audio amplifier innovation, distinguished by their switch-mode operation that ensures exceptional efficiency, significantly surpassing older amplifier classes in terms of reduced heat output and power conservation. These amplifiers utilize advanced modulation techniques, such as pulse-width modulation, to deliver high-fidelity audio while maintaining compact sizes and low energy consumption. Notably, their efficiency often surpasses 90%, a testament to their advanced switched output stages. Furthermore, Class D amplifiers have made remarkable progress in minimizing total harmonic distortion plusnoise (THD+N), achieving levels comparable to those of Class A and AB amplifiers, which enhances their audio performance. This advancement has effectively addressed previous concerns about the cost of additional filtering, compliance with electromagnetic interference standards, and less-than-ideal THD+N figures. With ongoing enhancements in modulation and feedback strategies, Class D amplifiers continue to push the envelope in energy-efficient, high-quality sound amplification.

Chapter 03: THD+N Analysis in Class-D Audio Amplifier Circuits

III.1 Introduction:

Conventional amplifiers, despite their commendable linearity and simplistic design, grapple with subpar efficiency and dissipate energy in the form of heat. Conversely, Class-D amplifiers, renowned for their superior efficiency, have emerged as the predominant and mostpervasive choice in the market, progressively displacing their traditional counterparts.

Nevertheless, Class-D amplifiers encounter two formidable hurdles: their intricate architectureand inherent non-linearity, which culminate in significant noise generation. Author in [1] hasdeveloped a superior class D audio amplifier circuit within several experimented circuits and we analyzed THD+N spectrum using Orcad/Pspice and MATLAB. We undertook an exhaustive examination and analysis of these distinct Class D amplifier circuits, scrutinizing THD+N metrics to pinpoint the circuitry yielding the most favorable THD+N performance.

III.2 Class D amplifiers without feedback:

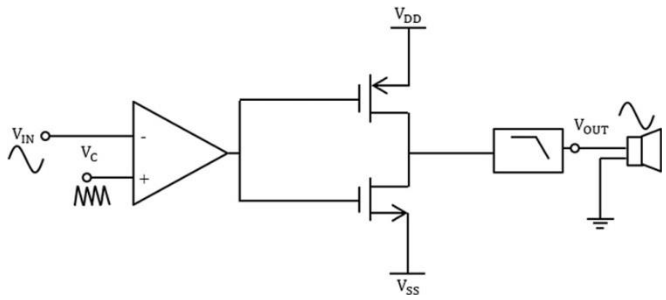

Figure 3.1: Basic circuit without feedback

The input signal has a modulation index of 0.9 and a frequency of 1 kHz. The output signal obtained is shown in Figure 3.2; despite its high amplitude, it has a major drawback: it is too noisy.

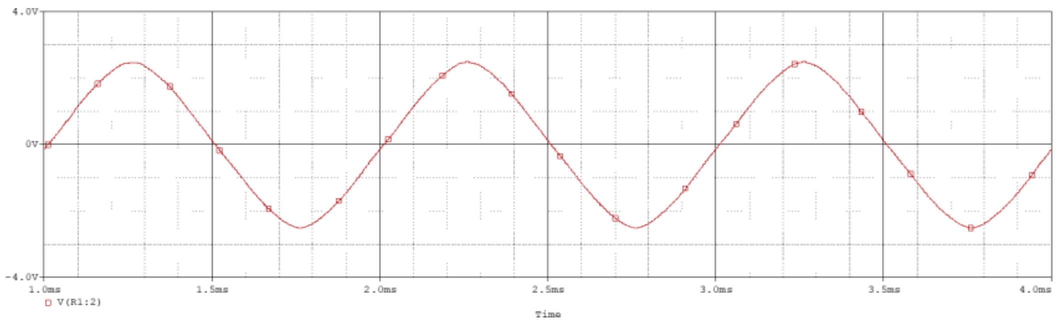

Figure 3.2: The output signal of circuit without feedback

The Total Harmonic Distortion plus Noise (THD+N) level as presented in Figure 3.3 is4.74% indicates a significant amount of distortion and noise in the output signal of the ClassD amplifier. This high THD+N value suggests that the unfiltered harmonics and other noise components are substantially affecting the purity of the fundamental 1 kHz signal, due to the absence of negative feedback.

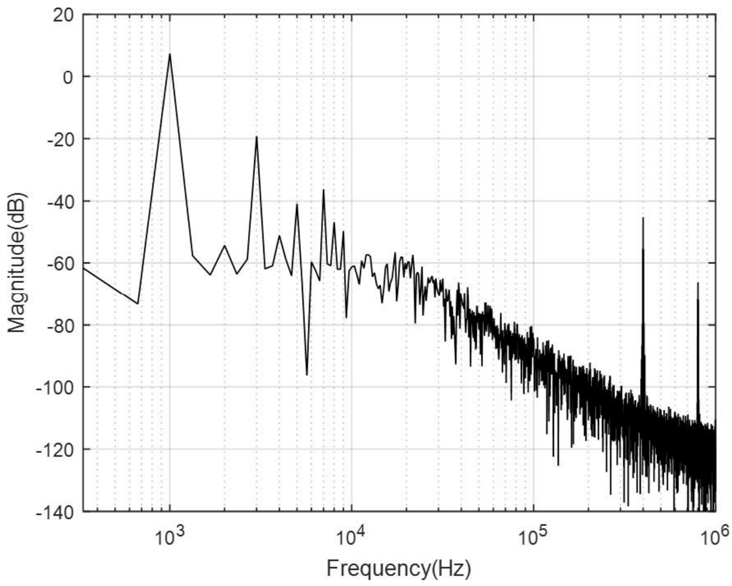

Figure 3.3: Basic circuit with usual feedback (Spectrum of the output signal)

III.3 The feedback in class D amplifiers:

Feedback in Class D amplifiers is essential for enhancing performance and stability. For example, feedback can reduce Total Harmonic Distortion plus Noise (THD+N) to less than 0.1%, compared to 1% in systems without feedback. The feedback mechanism ensures that the amplifier maintains consistent gain and fidelity, even under varying load conditions ranging from 4 to 8 ohms. Consequently, Class D amplifiers with feedback are better suited for high-fidelity audio applications, where precision and clarity are crucial.

III.3.1 CDA with usual feedback (first order integrator):

Class D amplifiers with usual feedback as presented in Figure 3.4, incorporating a first-order integrator, are a type of switching amplifier that uses pulse-width modulation (PWM) to achieve high efficiency. In this configuration, a portion of the output signal is fed back to the input through a first-order integrator. This feedback loop helps to stabilize the amplifier, reduce distortion and noise, and maintain consistent gain. The first-order integrator plays a crucial role in filtering and smoothing the signal, resulting in improved overall sound quality and performance. The output is taken from the PWM signal and feedback to the integrator. In a closed-loop configuration, the system remains stable, with the gain being stable even as it may decrease. Harmonics and noise decrease, and the amplitude of the output signal also diminishes.

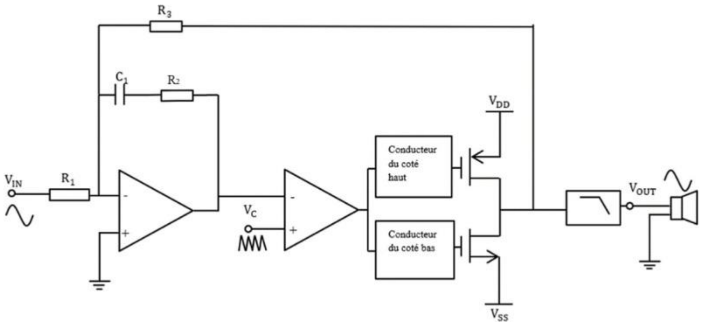

Figure 3.4: Basic circuit with usual feedback (first order integrator)

the input signal has a modulation index of 0.9 and a frequency of 1 kHz. The output signal obtained is shown in Figure 3.5; the noise significantly decreases using negative feedback loop. The Total Harmonic Distortion plus Noise (THD+N) is 0.22%.

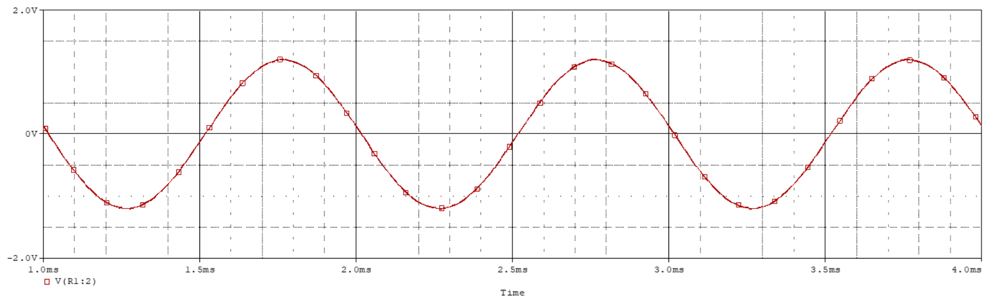

Figure 3.5: The output signal of circuit with usual feedback (first order integrator)

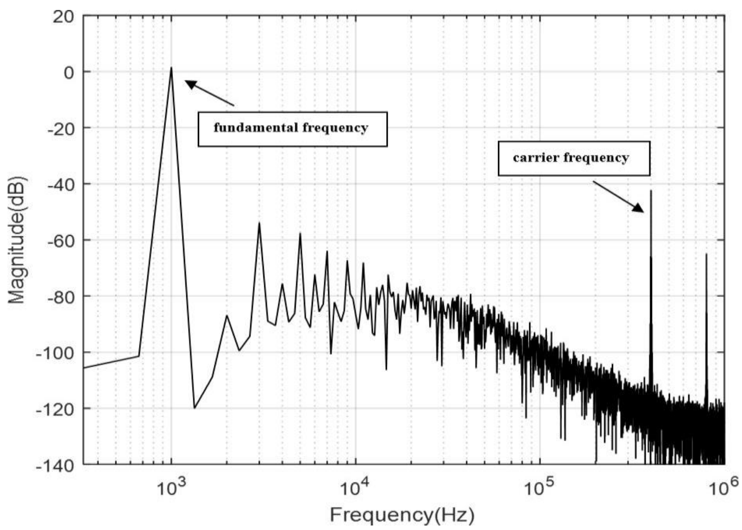

Figure 3.6: Spectrum of the output signal

III.3.2 CDA with usual feedback (second order integrator):

Class D amplifiers with usual feedback incorporating a second-order integrator as presented in Figure 3.7 are advanced switching amplifiers that use pulse-width modulation (PWM) for high efficiency. In this configuration, a portion of the output signal is fed back to the input through a second-order integrator. This feedback loop, with its double integration process, helps to further stabilize the amplifier, significantly reduce distortion and noise, and maintain consistent gain. The second-order integrator provides more effective filtering and smoothing of the signal compared to a first-order integrator, resulting in superior sound quality and overall performance.

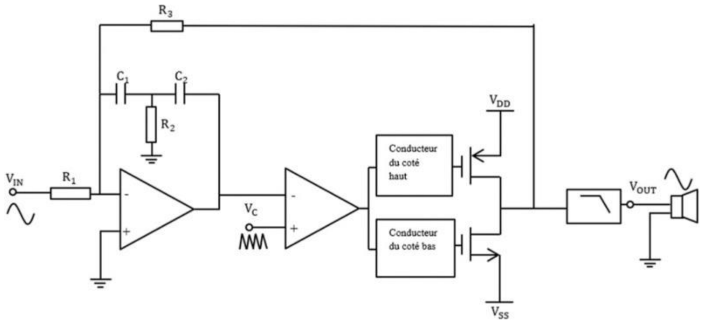

Figure 3.7: Class D amplifier with usual feedback (second order integrator)

The input signal, characterized by a modulation index of 0.9 and a frequency of 1 kHz, results in an output signal as depicted in Figure 3.8. Although the amplifier operates ata high amplitude, it is not particularly noisy. Nevertheless, there is a marginal reduction in noise level when compared to the typical feedback circuit that employs a first-order integrator. The exceptionally low noise level of the amplifier is reflected in the Total Harmonic Distortion plus Noise (THD+N) measurement, which stands at a mere 0.011%.

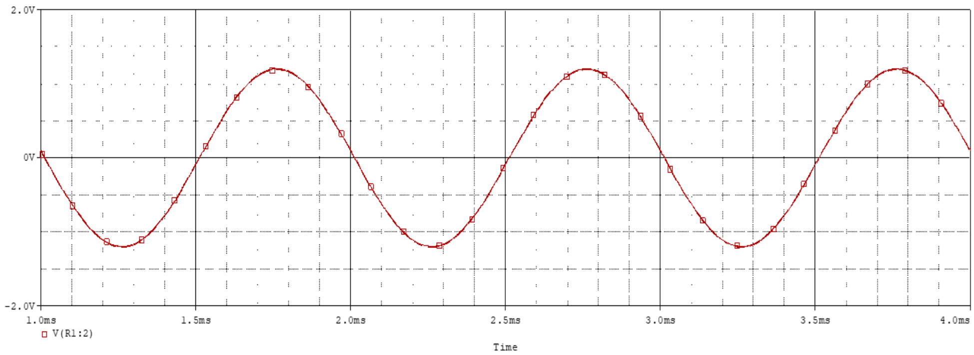

Figure 3.8: The output signal of circuit with usual feedback (second order integrator)

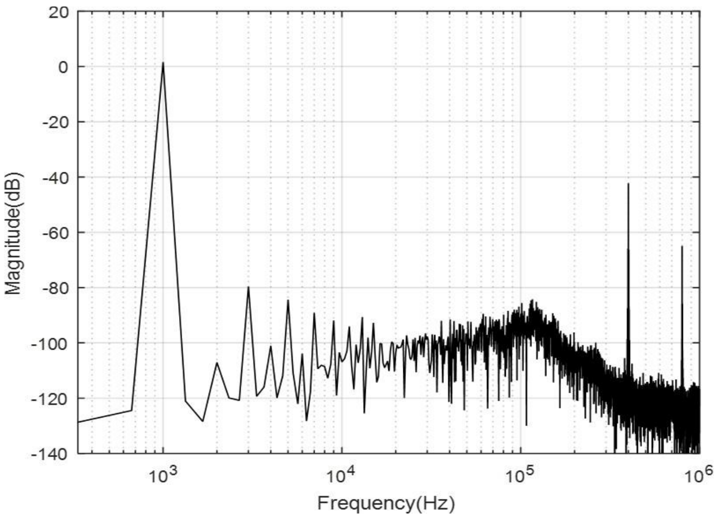

Figure 3.9: Spectrum of the output signal

III.3.3 CDA with novel feedback:

The different between the usual feedback and the novel feedback is adding a capacitor connected with the resistor in the feedback loop. We conducted a study with our supervisor author in [1] variation in the THD+N ratio in both types: Class D amplifier with novel feedback (first-order integrator) and Class D amplifier with novel feedback (second-order integrator). Below is a presentation of the results extracted from each circuit.

III.3.4 CDA with novel feedback (first order integrator):

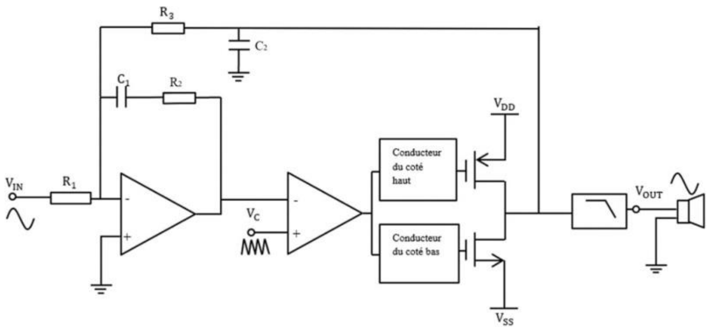

Figure 3.10: Diagramme of Class D amplifier with novel feedback (first order integrator)

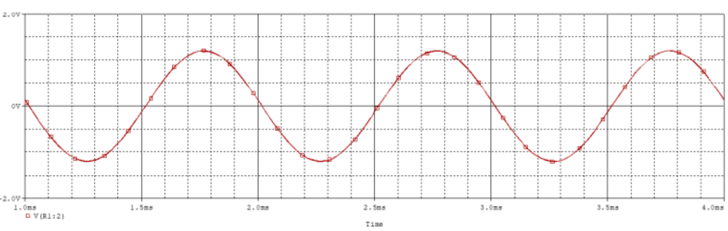

Figure 3.11: The output signal of circuit with Novel feedback (first order integrator)

The input signal, with a modulation index of 0.9 and a frequency of 1 kHz, the output signal illustrated in Figure 3.11. Although the amplifier delivers a high amplitude output, it remarkably does not exhibit significant noise. Moreover, when compared to the usual feedback circuit, the noise level is modestly decreased.

The Total Harmonic Distortion plus Noise (THD+N) is 0.011.

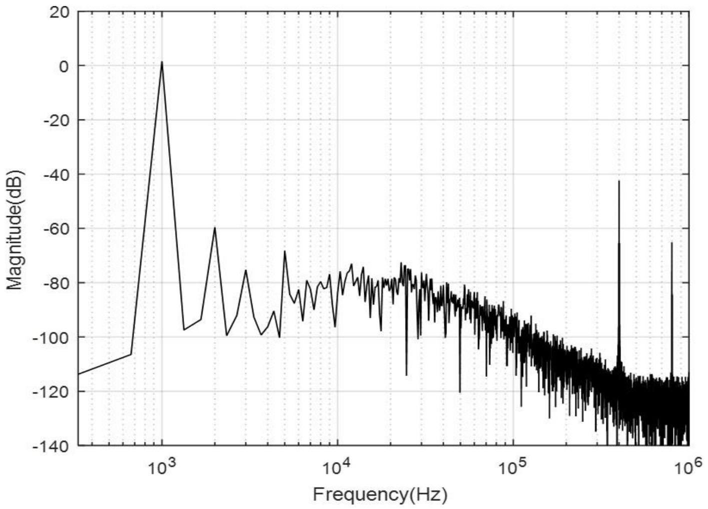

Figure 3.12: Spectrum of the output signal

III.3.5 CDA with novel feedback (second order integrator):

Class D amplifiers with novel feedback incorporating a second-order integrator as presented inFigure 3.13 represent an advancement in amplifier technology. By integrating a novel feedbackmechanism, typically in the form of a second-order integrator, into the Class D amplifier circuitry, performance enhancements are achieved. This feedback loop allows for the correction of errors and the extreme reduction of distortion and noise in the output signal. This Class D amplifier with novel feedback incorporating a second-order integrator provides us with the best THD+N of all, as we will illustrate in the following results.

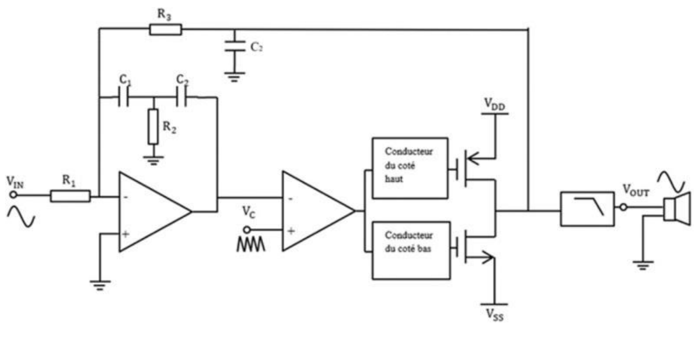

Figure 3.13: Diagramme of Class D amplifier with novel feedback (second order integrator)

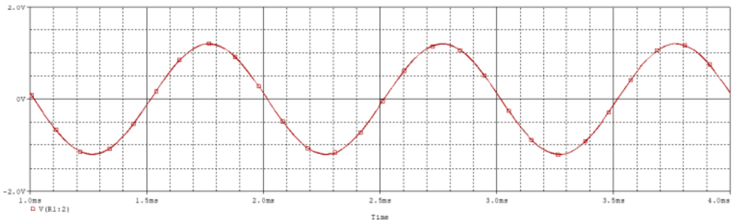

Figure 3.14: The output signal of circuit with Novel feedback (second order integrator)

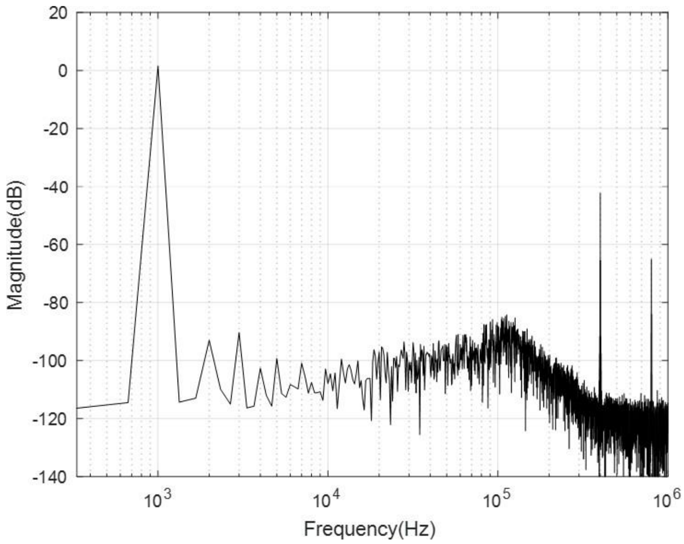

Figure 3.15: The output signal of circuit with Novel feedback (Spectrum of the output signal)

In this circuit, we achieved a THD+N of 0.004%, which is the best ratio compared to allprevious results, ensuring minimal noise distortion in the signal.

With a THD+N value of 0.004%, this indicates a very clean and accurate reproduction of the audio signal at the fundamental frequency of 1kHz, with minimal interference fromharmonics or noise.

Regarding integrators, the difference between a first-order and second-order integrator lies in their frequency response. A first-order integrator provides a roll-off rate of 20 dB/decade, while a second-order integrator offers a steeper roll-off rate of 40 dB/decade. This means that a second-order integrator is more effective at filtering out higher-order harmonics, which can result in a cleaner output signal with lower THD+N levels when used in Class D amplifier feedback loops.

III.4 Conclusion:

After thorough analysis of the obtained results from various circuits, it is evident that the integration of feedback mechanisms, plays a pivotal role in shaping the performance of Class D amplifiers. These feedback mechanisms serve to correct errors and mitigate distortion, resulting in improved signal fidelity. The circuits incorporating novel feedback designs consistently outperformed those lacking feedback, showcasing notable reductions in Total Harmonic Distortion plus Noise (THD+N) levels. Notably, the circuit featuring a second-order integrator demonstrated the most impressive outcome, achieving an exceptional THD+N ratio of 0.004%. This remarkable performance underscores the significance of innovative feedback techniques in achieving superior audio quality and minimizing signal distortion.

General Conclusion

In conclusion, our study has thoroughly explored power amplifiers, and their different classes, focusing particularly on Class D amplifiers. It has highlighted their significant advantages in efficiency and minimized power dissipation compared to traditional amplifiers. These characteristics make Class D amplifiers ideal for high-power applications in audio amplification, portable devices, and automotive systems.

Our study also delves into design methodologies and modulation techniques, focusing on feedback and its mechanisms, which enhance amplifier performance in terms of fidelity, stability, and noise suppression. By optimizing these mechanisms, we achieved significant improvements in THD+N performance, ensuring that Class D amplifiers deliver superior audio quality across different output levels.

Overall, Class D amplifiers represent a promising direction for energy-efficient and high-performance amplification technologies. These amplifiers operate with remarkable efficiency, minimizing power consumption and heat generation compared to traditional analog amplifiers. As a result, they find applications in various industries, especially where cost savings and environmental considerations are paramount.

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