Class D Amplifiers

Acknowledgements: Developed by Palmerino Mazzucco, Faculty of Mesa Community College, Mesa Arizona.

Special Notes: This Drill Down should be done as a pre-lab activity before the Multisim Class D Amplifier Interactive Simulation or the Class D Amplifier Lab.

Time Required: 3 hours

Equipment & Tools

- Internet connection
- Standard browsing (web surfing) capabilities

Team or Individual: This is an individual activity but students should share their research findings.

Learning Objectives

1. Differentiate between classes of amplifiers.
2. Describe the advantages of using MOSFETs in class D amplifiers.
3. Use a search engine to find information about amplifier chips.
4. Describe the use of class D amplifier chips in common devices such as PDAs, cell phones, laptops, hearing aids, or MP3 players.
5. Describe the limiting factors for classes of amplifiers.
6. Research class D amplifier product implementation and applications.

Performance and Task Procedures

The information in the Reading Assignment is used to supplement the information provided in the Switching Amplifier module and to introduce concepts that will be used in the Multisim simulation lab as well as the physical lab activity. Read over the information and answer the questions at the end. Use the internet to research the use of class D amplifiers in PDAs, cell phones, laptops, hearing aids, or MP3 players. Prepare either a written or oral report to share with the class.

Deliverables

- Answers to the questions following the Reading Assignment
- Written or oral report on a device that uses a class D amplifier

Scoring or Grading Criteria: The decision to grade students on their deliverables is left to the instructor. The length of the report and format is up to the instructor.

Reading Assignment

Class D amplifiers were initially introduced nearly 50 years ago. Today, because saving electrical power is a major concern, the use of class D amplifiers has moved to the forefront in the use of battery powered equipment.

In the past, class D amplifiers were considered inferior to many other amplifier configurations and limited to lower bandwidth applications such as telephones and public address (PA) systems. Advances in semiconductor devices combined with consumer demand for higher battery power performance has resulted in the advancement of class D technology. Today class D amplifiers are used in power compact systems such as hearing aids, PDA's, LCD TVs, MP3 players, car stereos, and mobile phones where battery life can be extended by as much as 2.5 times.

In fact, over the last several years advances in semiconductor fabrication processes have made fully integrated class D amplifiers possible. The integration of analog circuitry with fast-switching, high input and low output impedance MOSFET (Metal Oxide Semiconductor Field Effect Transistor) devices has furthered the evolution of the class D amplifier. Once discrete output power stages and supporting circuitry are now integrated in one chip. The resulting class D device is an effective and highly efficient solution for battery powered amplifier applications.

Often, amplifiers are used in the audio frequency spectrum (20 Hz to 20 kHz) where music and voice are amplified to higher power levels. This type of amplifier is called an audio power amplifier and is optimized to drive low-impedance loads such as headphones and stereo speakers. There are several amplifier topologies that amplify audio signals but the popularity of class D continues to rise due to its numerous advantages.

With efficiency levels in the area of 90% or beyond possible, class D amplifiers deliver a lower cost system with lower operating temperatures, longer battery life, lower power supply voltages, lower power levels, and better heat dissipation than most other competing amplifier classifications. Class D chips, chipsets, and evaluation boards are available with significant design support allowing users to rapidly implement new product designs.

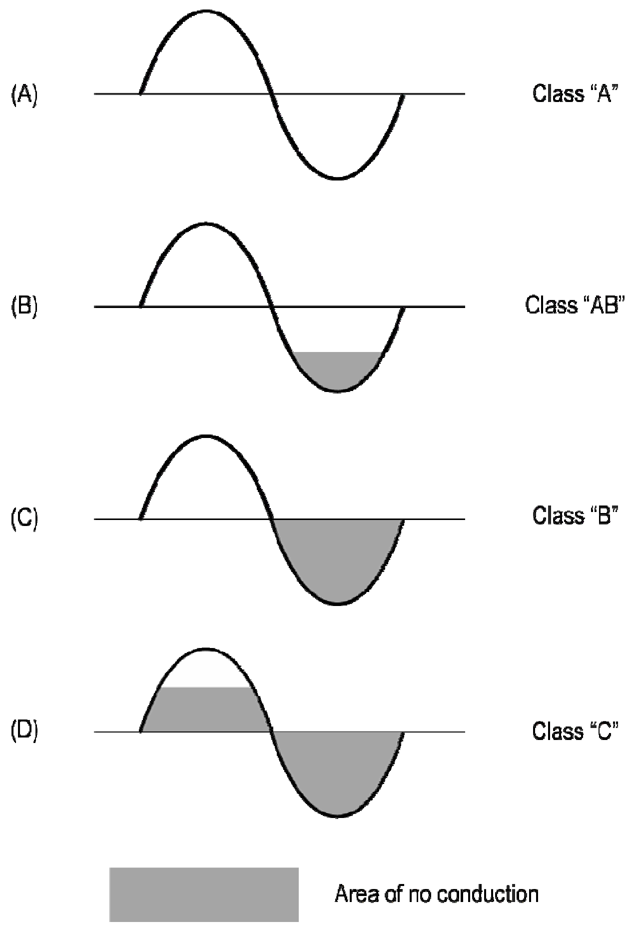
Switching vs. Linear Amplifiers

The class D amplifier is not an amplifier in the traditional sense of a linear amplifier circuit such as class A, B, and AB amplifiers.

Linear amplifiers produce an instantaneous output equal to a given input (V_{in}) multiplied by a constant (β or h_{fe}) known as gain. They require a DC biased transistor to operate in the linear region to amplify an input signal without clipping and distortion. The DC biasing of a transistor in linear mode results in a DC bias voltage drop directly across the amplifying transistor collector-emitter for a bipolar junction transistor (BJT) or the source-drain of a field effect transistor (FET) device. DC bias voltage across the transistor amplifier and the resulting current flow is present whether or not an input signal is driving the input of the amplifier.

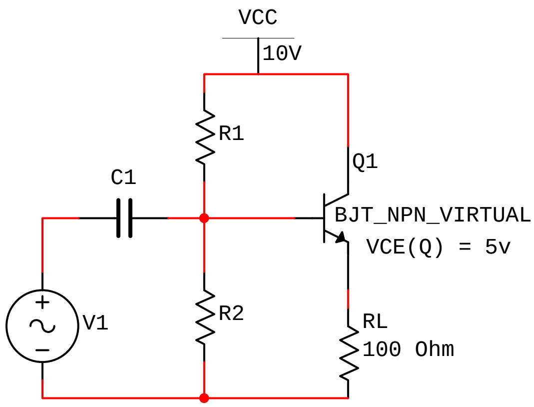
Power is dissipated continuously in a biased linear amplifier circuit where the transistor conducts for as much as 360^{o} of the input cycle. This continuous current flow, though not required by the load, results in power dissipation in the form of heat. This results in the requirement for a heat sink to transfer excessive heat to the ambient air when large power levels generated.

Before discussing functionality of a class D amplifiers, a review of class A, B, AB, and C amplifiers would be beneficial to place them in proper comparison with class D amplifiers.



Amplifier Operation and Conduction Time

Class A amplifiers are linear amplifiers that are biased "ON" to operate for 360^{o} of the input cycle time whether there is an RF signal present at the input or not. As a consequence, the amplifier draws current and therefore generates heat continuously. In spite of this, properly designed class A amplifiers offer no cross over distortion, good low output impedance, and high input impedance characteristics. Unfortunately class A amplifiers offer poor operating efficiency. Efficiencies of less than 25% in terms of power consumed compared to the power delivered to the load are common. It is quite often far less than 25% because maximum power is only delivered when the input signal reaches its peak level. In essence, 75% or more of the power consumed in a class A circuit dissipates as heat and does not reach the load. This can be tolerated at low power levels but, as power levels rise, the increased temperature can destroy the circuit.



Class A Amplifier

In the class A common-collector amplifier (emitter follower) shown, the circuit will provide power gain but the overall efficiency is poor. Let's calculate P_{in}, $P_{out\ (max)}$ and maximum efficiency of this amplifier.

P_{in} is equal to the power the DC supply delivers. Since the current will vary around the Q-point of the amplifier, the average current is equal to the quiescent current flow (Q-point current flow).

$$P_{in} = P_{DC} = I_{C(Q)} \text{ x } V_{CC} = 50 \text{ mA x } 10 \text{ V} = 500 \text{ mW}$$

Maximum power will occur when the input signal V1 is at its maximum peak across the load. Since in this circuit the Q-point voltage V_{CE} is ½ V_{cc}, the voltage at the load can swing from +5v at cutoff and -5v at saturation resulting in a +10 $V_{p\text{-}p}$ maximum voltage swing across the load before clipping occurs. (AC power is calculated using RMS values.)

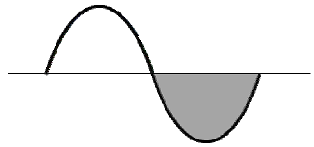
$$V_{out\ (RMS)} = V_{out\ (peak)} \text{ x } 0.707 = 5\ V_p \text{ x } 0.707 = 3.5\ V_{(RMS)}$$

$$P_{out} = V_{out\ (RMS)}{}^2/R_L = 3.5V^2 / 100\ \Omega = 125 \text{ mW}$$

Since the input voltage swing is usually less than the full range, the efficiency will be even lower. Small power levels in the milliwatt level with poor efficiency can be tolerated. At higher power ratings, poor efficiency quickly becomes unacceptable since power not consumed by the load must be absorbed by the circuit components in the form of heat.

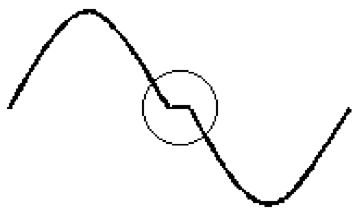
Finally, maximum efficiency is

$$\text{Efficiency} = P_{out}/P_{in} \text{ x } 100\ \% = 125 \text{ mW} / 500 \text{ mW x } 100\ \% = 25\ \%$$



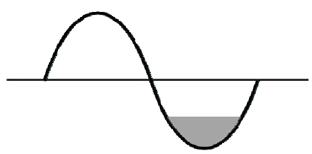
Class B Amplifier and Conduction Time

Class B amplifiers are designed around a push pull configuration using two transistors. They are more efficient (ideally 78.5%; realistically 65-70%) than class A. The basis of operation for a class B amplifier is based around two transistors driving the load. Only one transistor turns ON at a time depending on the positive or negative alternation of the input signal. This arrangement increases efficiency at the expense of increased cross over distortion.



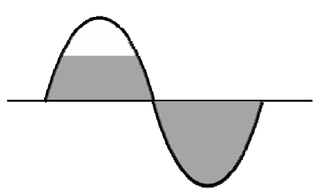
Cross Over Distortion, Class B Amplifier

Cross over distortion affects output signal quality. Cross over distortion occurs as the input signal transitions to levels that result in the switching between the outputs of one transistor and then the other and vise versa.



Class AB Amplifier and Conduction Time

Class AB amplifiers combine features of class A and B and reduce the problems of cross over distortion. This is accomplished by providing a DC bias voltage at the base of each transistor. This places the input voltage of each device at levels just above their fully OFF state leaving both transistors partially biased ON. The transition between each transistor turning ON and OFF becomes smoother. Decreased crossover distortion comes at the expense of efficiency of operation which is ideally 60% but 45-55% realistically.



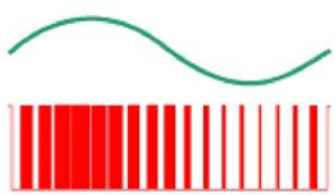
Class C Amplifier and Conduction Time

Class C transistor operation is quite different from that of class A, B, and AB amplifiers. Class C amplifiers are purposely biased below cutoff, and operate in linear mode for brief periods of time. The output current flows for less than 180° of the input but the input signal is not truly reproduced at the output. The current drawn is proportional to the RF output power level which results in a very good efficiency. Unfortunately, class C amplifiers are limited to RF (radio frequency) circuits that use resonant tuned circuits and oscillator. The short duration current pulses into the amplifier energize the load (a resonant circuit) causing oscillations. Efficiencies can reach 90% which makes them effective in RF transmitters designed to output kilowatts of signal power.

Class D Amplifiers

Although class D switching amplifier waveforms resemble the form of digital logic switching circuit operation, the D does not stand for digital. Class D amplifiers operate with extremely high efficiency. This efficiency directly translates to about 50% heat savings compared to a comparable linear amplifier. Ideal efficiency of a class D is 100% while the realistic efficiency of a class D amplifier can approach 90% and beyond over its full dynamic signal range. The same cannot be said about rival amplifier topologies which often exhibit somewhat higher efficiencies only at their peak output power levels.

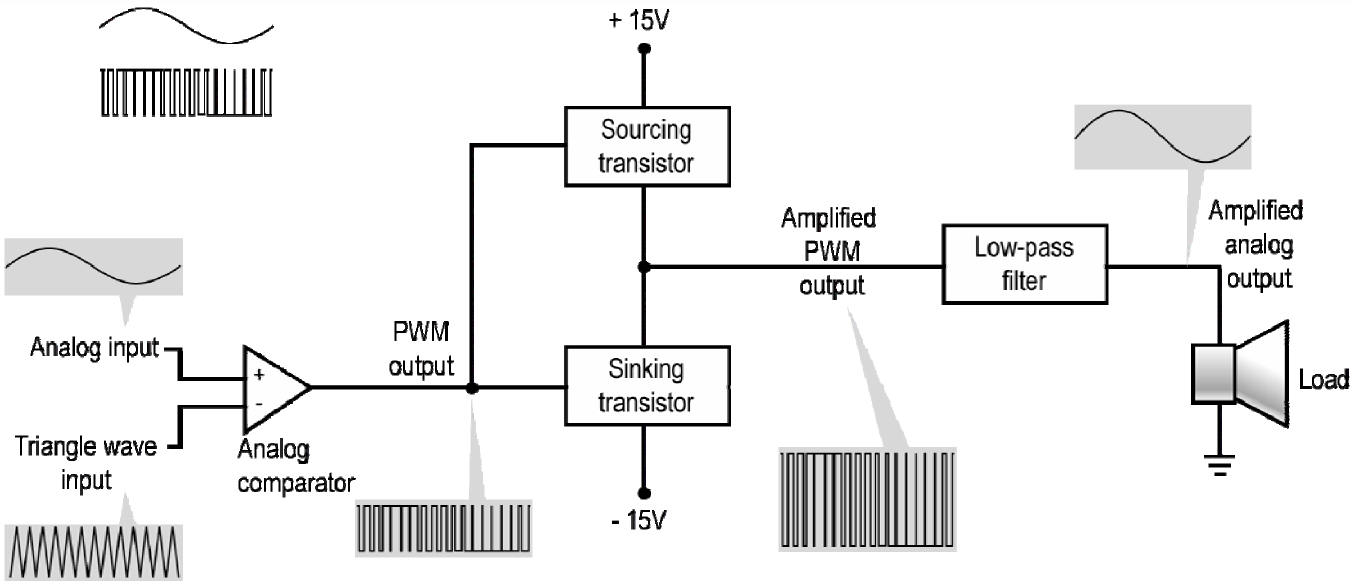
So how does a class D amplifier remain so cool and efficient and still amplify? The secret lies in its modulation technique pulse width modulation (PWM). PWM controls the on/off switching action of the power switching transistors that provide power to the load. The intelligence, or voltage level, of a given input signal is encoded as a pulse width.



Pulse Width Modulation

Class D amplifier designs incorporate the use of transistor devices as switches much what is used in the design of switching power supplies and the manufacture of computer microchips.

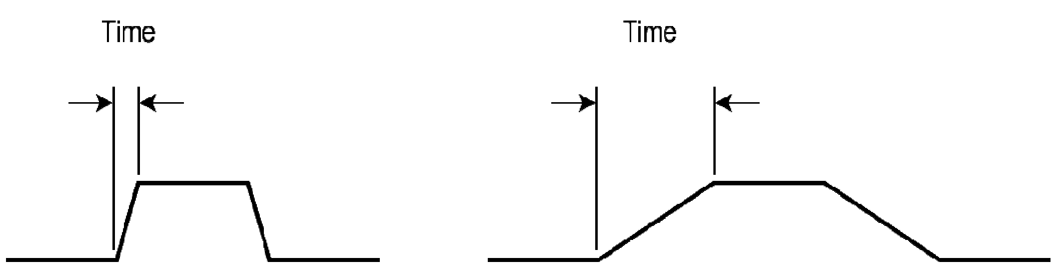
There are two MOSFET devices at the heart of the circuit connected in a similar fashion to the output of a class AB amplifier. One discrete implementation of a class D amplifier configuration has one MOSFET operating as a sourcing transistor while the other acts as the sinking transistor.



Class D Amplifier and Waveforms

Just like a class B amplifier design, there is never more than one MOSFET on at a time providing switching action and power to the load continuously. MOSFETS used as switches operate outside the linear region most of the time assuming one of two states: ON or OFF. If a pair of BJT devices is used to do the switching instead of the MOSFETs, it is called cutoff and saturation. This is where the magic of the class D amplifier begins. Efficiency remains high at all times because a MOSFET used as a switch develops very little voltage drop across its switching terminals during the ON state and maximum power transfers to the load. During the OFF state, zero current flows through the MOSFET and power dissipation is minimal.

Class D amplifiers spend as little time as possible in linear mode, where precious current flow and power is wasted transitioning between the ON and OFF states. The MOSFET offers a simple design implementation as a switch, faster switching times, and excellent input and output impedance characteristics when compared to similar BJT devices.



a. MOSFET Device b. Bipolar Junction Transistor Device

Switching Waveforms

Component specification sheets available in data books and over the internet can be used to compare MOSFET and BJT devices switching speed data. We will use the general purpose NPN transistor, 2N3904 and the International Rectifier Enhancement Mode MOSFET IRF530N for our discussion. Links for the data sheets for these transistors are available in the Reference section of this module.

Symbol	Parameter	Test Conditions	Minimum	Units
t_d	Delay Time	$\mathbf{V_{CC} = 3.0\ v}$, $V_{BE} = 0.5$ v, $I_C = 10$ mA	35	ns
t_r	Rise Time		35	ns
t_s	Storage Time	$\mathbf{V_{CC} = 3.0\ v}$, $I_C = 10$ mA	200	ns
t_f	Fall Time		50	ns

BJT General Purpose Amplifier 2N3904 Switching Characteristics

Symbol	Parameter	Test Conditions	Minimum	Units
$t_{d(on)}$	Turn-On Delay Time	$\mathbf{V_{DD} = 50\ v}$	9.2	ns
t_r	Rise Time	$I_D =$ 9.0A	22	ns
$T_{d(Off)}$	Turn-Off Delay Time	$R_G =$ 12 Ω	35	ns
t_f	Fall Time	$V_{GS} = 10$ v	25	ns

Enhancement Mode MOSFET IRF530N Switching Characteristics

The table for the 2N3904 shows that the switching speed for rise (t_r) and fall (t_f) times range from 35-50 ns for a signal switching at voltage levels of V_{CC} = 3v. In comparison, rise and fall times of the IRF530N MOSFET at first glance appear to be very similar at 22-25ns. What is somewhat less apparent when viewing the data sheet is that the MOSFET test data is for a signal switching at voltage levels of V_{DD} = 50 v. In other words, we are not comparing the times 1:1 over the same voltage levels. The difference in test voltages of 3v and 50v places the rise and fall times of both devices at about 17:1 (ratio of V_{DD} / V_{CC} = 50v/3v = 16.666).

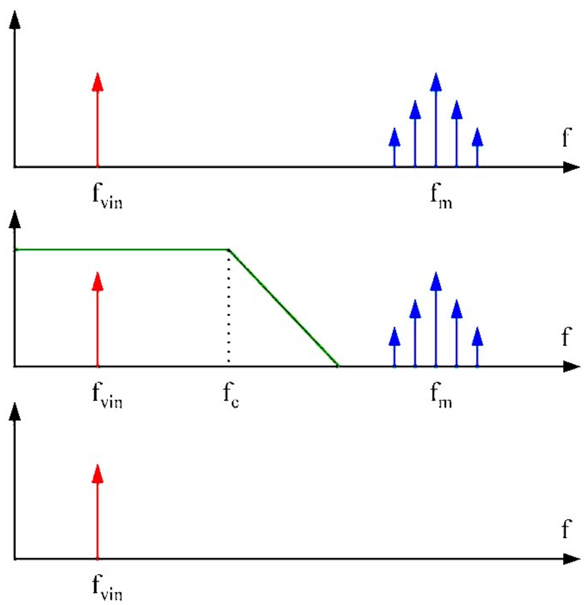
Under close to identical situations, the 2N3904 would require 17 x (35-50ns) or somewhere between 595 - 850 ns time to switch. To extend the switching voltage level and rise and fall times in a linear fashion to 50v and re-analyze the switching speeds, we must multiply the data sheet values for rise and fall times of the 2N3904 by 17.

In summary, the 2N3904 operates with rise and fall switching times of over 595 ns to switch to 50v while the IRF 530N MOSFET could do it 17X faster at 22 - 25 ns. The data clearly shows the ability of the MOSFET device to switch faster under identical conditions.

In addition, the 2N3904 suffers from storage time delays of 200 ns. This consumes even more time. MOSFET device structure is different from that of a BJT and does not suffer from storage time issues. The numbers presented clearly show the faster switching speed MOSFETs offer. Actual rise and fall time performance of BJT or MOSFET devices depends on the part chosen in each case, and will vary between different device models.

The final stage of the class D amplifier consists of a low pass filter. The low pass filter is a very important and integral part of the class D amplifier architecture. The design of the low pass filter can play an important part in determining the overall efficiency of the amplifier. For this reason, the low pass filter uses reactive components to keep power dissipation to a minimum in the filter circuit. Capacitors and inductors dissipate zero average power and therefore do not dissipate power like a resistive load or filter would do. Reactive components consume power on one half of one input cycle and return the power to the circuit on the other.

There are a minimum of two frequencies present at all times at the output of the class D amplifier. First, there is the triangle wave sample frequency which often runs at 250 kHz or faster. Second, there is the frequency of the information being fed into the class D amplifier.

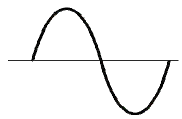
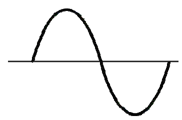
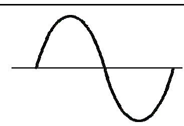
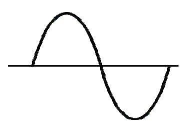
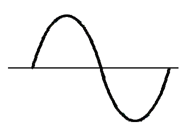


Frequency Domain Plot: Data vs. Modulation Frequency

The top graph above represents a frequency domain plot of the voltage into the amplifier at a given f_{Vin} frequency and the spectral response of the modulated triangle wave. The center graph above shows how the low pass filter encapsulates the desired analog input while removing the high frequency PWM carrier out beyond the -3dB cutoff of the low pass. In some cases, there can be residual noise in the output signal as a result of the low pass not doing such a good job and it can affect output quality levels of the amplified output signal. Finally, the bottom graph shows the actual frequency that exits the output filter is the original signal sent into the class D amplifier.

Drill Down Questions

1. Complete the following table comparing class A, B, AB, C, and D amplifiers.

Class	% Efficiency	Conduction Time	Disadvantages	Advantages
A				
B				
AB				
C				
D				

2. Why is a heatsink required in linear amplifiers?

3. List two types of circuits where class C amplifiers are used.

4. How does a class D amplifier remain cool and efficient and still amplify?

5. Compare the use of MOSFETs as switches to BJTs in class D amplifiers.

6. What is the purpose of the low pass filter in the class D amplifier?

7. Can a BJT NPN and PNP transistor pair be used in place of the MOSFET devices used in a class D amplifier to provide the switching action required? If so, what would be the tradeoff of using such a configuration?

8. List at least 3 benefits of a more efficient amplifier operation.

9. State at least 3 applications of class D amplifiers.

10. Your boss asks you to suggest an amplifier design for an application that amplifies a signal in the frequency range of (20 Hz to 20 kHz) using a small 9v battery. The following criteria must be met: low cost, small physical space for mounting the circuit, and light weight. The circuit will generate moderate levels of power. What class amplifier do you recommend?? In complete sentences, identify your choice and back it up with proven information about your choice.

11. Use a search engine such as google.com, yahoo.com or similar and enter the key search words “Class D Amplifier Chip” and spend some time finding the part number and cost of at least 3 class D amplifier chips. Fill in the blanks below:

Part Number	Manufacturer	Cost (ea.)

Drill Down Report

Use the Internet and a search engine to find an application for class D amplifiers. Use the following key word examples: class D amplifier (choose one of the following or one of your own: hearing aid; PDA; cell phone; MP3; laptop; car stereo). Research at least three articles and prepare a short report to summarize your findings with the class. Include photos, data sheets, tables, or graphs where appropriate. Use the following table to help organize your report.

Application:		
Link or Article	Advantages of class D Amplifier	Facts