

# Power Amplifiers

## Introduction to Power Amplifiers

What you'll learn in Module 5.

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Understand the Operation of Power Amplifiers.

[Section 5.1 Power Transistors & Heat Sinks.](#)

- Power Transistor Construction.
- Power De-rating & High Power Operation.
- Thermal Resistance of Heat Sinks.
- Thermal Runaway.

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- Transformer coupled Class A power output stages.

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- Class B biasing.
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- Driver transformers.
- Transistor phase splitter stages.
- Emitter coupled phase splitter.
- Transformerless push-pull.

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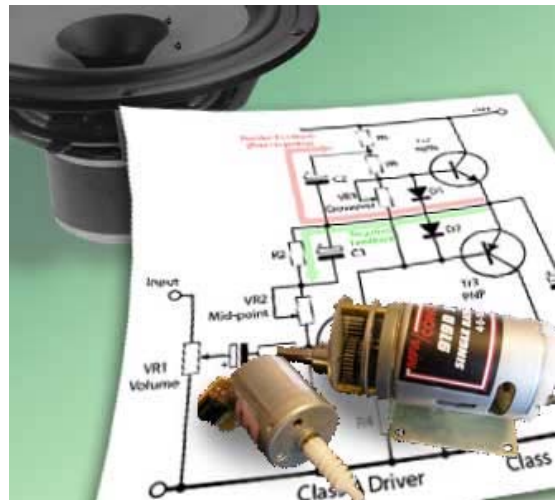
- Complementary Outputs.
- Temperature & DC stabilisation.
- Mid-point & crossover adjustment.
- NFB & Bootstrapping.

[Section 5.6 Amplifier Classes C to H.](#)

- Class C operation.
- Class D Power Amplifier operation.
- Class E & F Power Amplifiers.
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- Test your knowledge and understanding of Power Amplifiers.



### Power Amplifiers

Amplifier circuits form the basis of most electronic systems, many of which need to produce high power to drive some output device. Audio amplifier output power may be anything from less than 1 Watt to several hundred Watts. Radio frequency amplifiers used in transmitters can be required to produce thousands of kilowatts of output power, and DC amplifiers used in electronic control systems may also need high power outputs to drive motors or actuators of many different types. This module describes some commonly encountered classes of power output circuits and techniques used to improve performance.

The voltage amplifiers described in Amplifiers Modules 1 to 4 can increase the amplitude of a signal many times but may not, on their own, be able to drive an output device such as a loudspeaker or motor.

For example a voltage amplifier may have a gain of 100 and be able to amplify a 150mV signal to an amplitude of 15V and it is quite possible that the amplifier can feed that 15V signal into a load of say 10K $\Omega$ , but if the load is changed to a value of 10 $\Omega$ , the voltage amplifier would not be able to provide the extra current needed to maintain an output voltage of 15V across 10 $\Omega$ .

Likewise, a current amplifier may have a gain of 100 and be able to amplify a 10 $\mu$ A signal to 1mA at a very low output voltage, but be unable to supply a 1mA signal at say 10V.

In either case the voltage or current amplifier does not have sufficient POWER (volts V x current I). Voltage and current amplifiers can make use of small transistors and do not draw large amounts of power from the power supply in order to amplify signals by often, very large amounts. However the small transistors they use have very tiny junction areas and so cannot handle the power needed to drive some output devices without overheating.

Module 5.1

## Power Transistors & Heat Sinks

What you'll learn in Module 5.1

**After studying this section, you should be able to:**

Recognise power transistor construction.

- Understand the need to connect the collector and metal case.

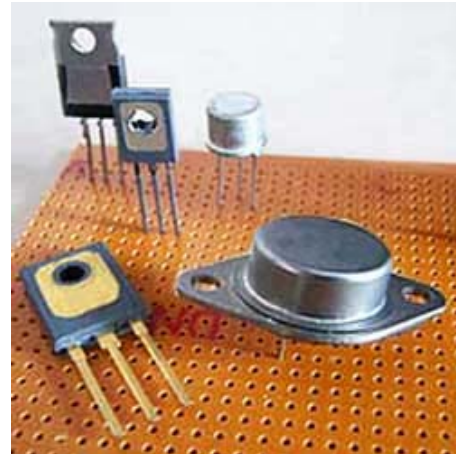
Understand the relationship between power and temperature in power transistors.

- Power De-rating.

Understand the need for heat sinks.

- Methods for choosing heat sinks.
- Methods for fitting heat sinks.

Calculate Thermal Resistance requirements for heat sinks.



Power Transistors

There is not a clear cut difference between ‘ordinary’ transistors used in voltage amplifiers and power transistors, but generally Power transistors can be categorised as those that can handle more than 1 Ampere of collector (or Drain in the case of FETs) current.

Because power transistors, such as those shown in Fig. 5.1.1 handle larger currents and higher voltages, they have a different construction to small signal devices. They must have low output resistances so that they can deliver large currents to the load, and good junction insulation to withstand high voltages. They must also be able to dissipate heat very quickly so they do not overheat. As most heat is generated at the collector/base junction, the area of this junction is made as large as possible.

### Power and Temperature

The maximum power rating of a transistor is largely governed by the temperature of the collector/base junction as can be seen from the power de-rating graph in Fig. 5.1.2. If too much power is dissipated, this junction gets too hot and the transistor will be destroyed, a typical maximum temperature is between 100°C and 150°C, although some devices can withstand higher maximum junction temperatures. The maximum power output available from a power transistor is closely linked to temperature, and above 25°C falls in a linear manner to zero power output as the maximum permissible temperature is reached.

## Power De-rating

For example, a transistor such as the TIP31 having a quoted maximum power output  $P_{TOT}$  of 40W can only handle 40W of power **IF** the case temperature (slightly less than the junction temperature) is kept below 25°C. The performance of a power transistor is closely dependant on its ability to dissipate the heat generated at the collector base junction.

Minimising the problem of heat is approached in two main ways:

1. By operating the transistor in the most efficient way possible, that is by choosing a class of biasing that gives high efficiency and is least wasteful of power.
2. By ensuring that the heat produced by the transistor can be removed and effectively transferred to the surrounding air as quickly as possible.

Method 2 above, highlights the importance of the relationship between a power transistor and its heat sink, a device attached to the transistor for the purpose of removing heat. The physical construction of power transistors is therefore designed to maximise the transfer of heat to the heat sink. In addition to the usual collector lead-out wire, the collector of a power transistor, which has a much larger area than that of a small signal transistor, is normally in direct contact with the metal case of the transistor, or a metal mounting pad, which may then be bolted or clipped directly on to a heat-sink. Typical metal cased and metal body power transistors are shown in Fig. 5.1.1

Because power amplifiers generate substantial amounts of heat, which is wasted power, they are made to be as efficient as possible. With voltage amplifiers, low distortion is of greater importance than efficiency, but with power amplifiers, although distortion cannot be ignored, efficiency is vital.

## Heat-sinks

A heat-sink is designed to remove heat from a transistor and dissipate it into the surrounding air as efficiently as possible. Heat-sinks take many different forms, such as finned aluminium or copper sheets or blocks, often painted or anodised matt black to help dissipate heat more quickly. A selection of heat-sinks is illustrated in Fig. 5.1.3. Good physical contact between the transistor and heat-sink is essential, and a heat transmitting grease (heat-sink compound) is smeared on the contact area before clamping the transistor to the heat-sink.

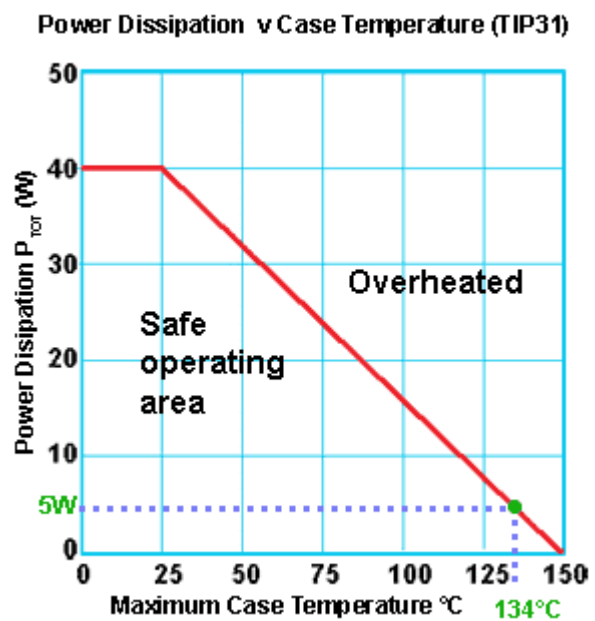


Fig 5.1.2 Power de-rating Graph for the TIP31

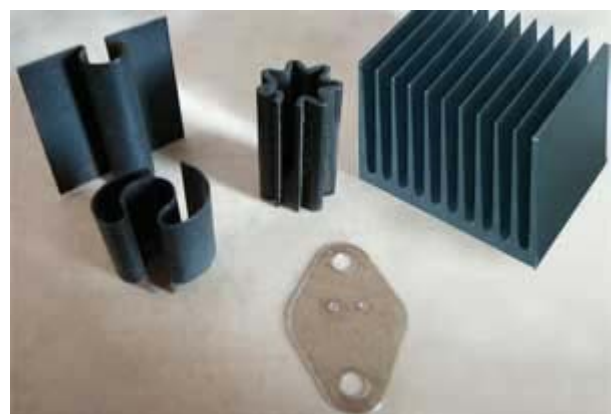


Fig 5.1.3 Heat-sinks

Where it is necessary to maintain electrical insulation between transistor and heat-sink a mica layer is used between the heat-sink and transistor. Mica has excellent insulation and very good heat conducting properties.

### Choosing the Right Heat-sink

Many heat-sinks are available to fit specific transistor package types, ('package' refers to the shape and dimensions of the transistor). Fig 5.1.4 shows the various stages in fitting a typical clip on heat-sink.

**a.** Shows a tube of heat-sink compound.

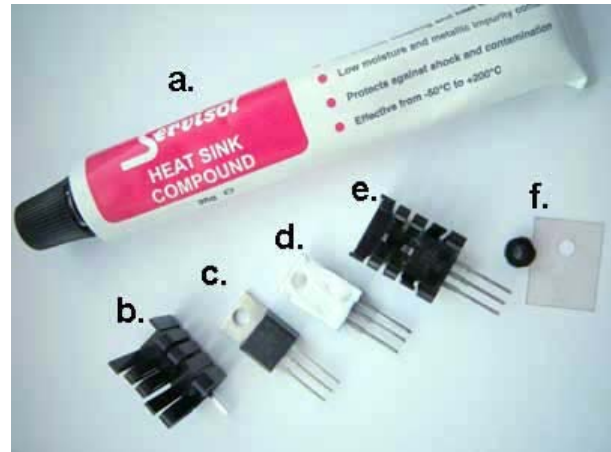
**b.** Shows a TO220 clip on heat-sink.

**c.** Shows a TIP31 transistor, which has a TO220 package type, ready for mounting.

**d.** Shows the metal body of the transistor smeared with heat-sink compound. This is essential to create efficient heat transfer between the transistor and heat-sink.

**e.** Shows the transistor fitted to the heat-sink.

**f.** Shows an alternative method of mounting, used when the metal body of the transistor, (which is usually also the collector terminal), must be insulated from the heat-sink. This example uses a TO220 shaped mica washer, and the transistor is clamped to the heat-sink with a bolt fitted through the small insulating bush.



**Fig 5.1.4 Fitting a TO220 Heat-sink**

### Calculating the Required Thermal Resistance $R_{th}$ for a Heat-sink

The heat-sink chosen must be able to dissipate heat from the transistor to the surrounding air, quickly enough to prevent the junction temperature of the transistor exceeding its maximum permitted value (usually quoted on the transistor's data sheet), typically 100 to 150°C.

Each heat-sink has a parameter called its Thermal Resistance ( $R_{th}$ ) measured in °C/Watt and the lower the value of  $R_{th}$  the faster heat is dissipated. Other factors affecting heat dissipation include the power (in Watts) being dissipated by the transistor, the efficiency of heat transfer between the internal transistor junction and the transistor case, and the case to the heat-sink.

The difference between the temperature of the heat-sink and the air temperature surrounding the heat-sink (the ambient temperature) must also be taken into account. The main criterion is that the heat-sink should be efficient enough, too efficient is not a problem.

Typical  $R_{th}$  Calculation for:

**A TIP31 transistor (TO220 package) required to dissipate 5 Watts.**

**Maximum Junction Temperature = 150°C**

**Ambient (air) temperature = 25°C.**

Thermal resistance between junction and case calculated from power de-rating graph Fig. 5.1.2.

$R_{th-j-c} = (150°C - 25°C) / 40W = 3.125°C.$

Max. case temperature when dissipating 5W =  $150 - (5 \times 3.125) = 134°C$  (approx).

Thermal resistance  $R_{th-c-hs}$  between case and heat-sink (allowing for mica washer) = 2°C.

Max. heat-sink temperature =  $134 - (5 \times 2) = 124°C.$

To reach ambient air temperature = 25°C Thermal resistance of heat-sink must be better than  $(124 - 25) / 5 = 19.8°C/W$

A better choice, to avoid operating the transistor at its **maximum** permitted temperature, would be to choose a heat-sink with a thermal resistance of about 10 to 15°C/W.

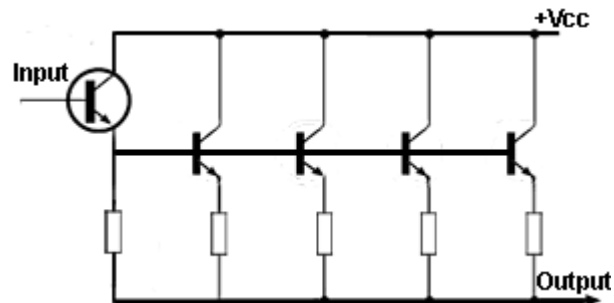
Therefore any heat-sink with a thermal resistance lower or equal to the calculated value should be OK, but to avoid continually running the transistor at, or close to the maximum permitted temperature, which is almost guaranteed to shorten the life of the transistor, it is advisable to use a heat-sink with a lower thermal resistance where possible.

The power de-rating graph for a [TIP31](#) transistor shown in Fig. 5.1.2 illustrates the relationship between the power dissipated by the transistor and the case temperature. When the transistor is dissipating 5W, it can be estimated from the graph that the maximum safe case temperature, for a junction temperature of 150°C would be about 134 to 135°C, confirming the above calculation of max. case temperature.

The TIP31 transistor has a maximum power dissipation  $P_{TOT}$  of 40W but it can be seen from the graph in Fig. 5.1.2 that this is only attainable if the case temperature of the transistor can be held at 25°C. The case temperature can only be allowed to rise to 150°C (the same as the maximum junction temperature) if the power dissipation is zero.

#### Parallel Transistors for High Power Applications

With high power applications it may be impossible to find a suitable heat-sink for a particular transistor, then one solution would be to use a different power transistor, or different case (package) type if available. Another alternative is to use two or more transistors connected in parallel, sharing the total power between them. This can be a cheaper option than a single very expensive heat-sink.



**Fig 5.1.5 Power Transistor Connected in Parallel**

#### Thermal Runaway

In many modern circuits power MOSFETs are preferred to BJTs because of the BJTs problem of thermal runaway. This is a process where current flow rises as a natural effect in semiconductors as the temperature of the device increases. This rise in temperature then leads to a further increase in current flow and a subsequent further rise in temperature, until the rise in temperature and current, spirals out of control and the device is destroyed.

When several poorly matched transistors are connected in parallel, the transistor initially passing the most current will get hotter, whilst the others, passing less current get cooler. Therefore the hotter transistor can be in danger of thermal runaway, however BJTs, carefully matched may still be preferable to MOSFETs for some high voltage applications.

## Module 5.2

## Class A Power Amplifiers

What you'll learn in Module 5.2

**After studying this section, you should be able to understand:**

The limitations due to the efficiency of class A power amplifiers.

- Efficiency of class A
- Effects on power supply requirements.

Transformer coupled Class A power output stages.

- The effect of an inductive load on  $V_{pp}$ .
- Impedance matching with transformer coupling.

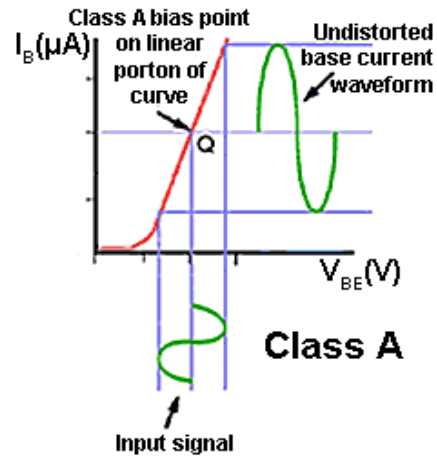


Fig 5.2.1 Class A Bias

### Amplifier Classes

The Class A Common Emitter Amplifier described in Amplifier Module 1, Module 2 and Module 3 has some excellent properties that make it useful for many amplification tasks, however its use as a power amplifier is limited by its poor efficiency. Although Class A may be used for power output stages (usually low to medium power), it is less used for higher power output stages, as more efficient classes of amplifier such as Classes B, AB or even classes D, E, F, G and H are available.

The classes A, B, AB and C refer to the way the amplifiers are biased, although class C is mainly used in oscillator circuits. Classes D to H are used in switch mode amplifiers where power is saved by having the output transistors switched rapidly between fully on and fully off. In either of these states the transistor is dissipating little or no power.

### Class A Power Amplifiers

The purpose of class A bias is to make the amplifier relatively free from distortion by keeping the signal waveform out of the region between  $0\text{V}$  and about  $0.6\text{V}$  where the transistor's input characteristic is non linear. Class A design produces good linear amplifiers, but are wasteful of power. The output power they produce is theoretically 50%, but practically only about 25 to 30%, compared with the DC power they consume from the power supply.

Class A power amplifiers use the biasing method illustrated in Fig. 5.2.1. This method causes a standing bias current to be flowing during the whole waveform cycle, and even when no signal is being amplified. The standing bias current (the Quiescent Current) is sufficient to make the collector voltage fall to half the supply voltage, and therefore power ( $P = I_C \times V_{CC}/2$ ) is being dissipated by the transistor whether any signal is being amplified or not. This was not a great problem in class A voltage amplifiers, where the collector current was very small, but in power amplifiers output currents are thousands of times larger, so efficient use of power is crucial.

## Transformer Coupled Class A Output

The circuit shown in fig 5.2.2 is a class A power output stage, but its efficiency is improved by using an output transformer instead of the resistor as its load.

The transformer primary winding has high apparent impedance ( $Z_P$ ) at audio frequencies because of the action of the transformer in 'magnifying' the impedance of the loudspeaker. As shown by the formula:

$$Z_P = Z_{LS} (N_P/N_S)^2$$

The apparent impedance of the primary winding ( $Z_P$ ) will be the actual impedance of the loudspeaker ( $Z_{LS}$ ) multiplied by the square of the turns ratio.

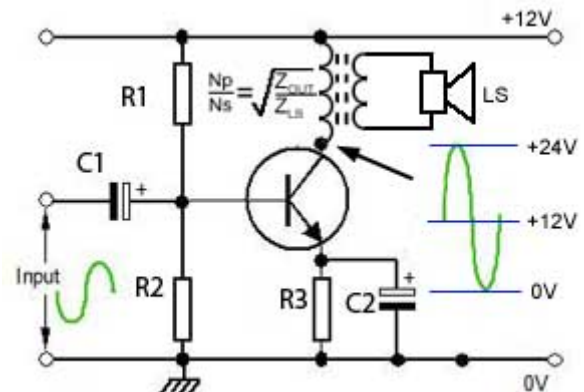


Fig 5.2.2 Basic Class A Power Amplifier

Although the impedance of the transformer primary winding is high, its DC resistance (at 0Hz) is practically zero ohms. Therefore while a class A voltage amplifier might be expected to have a collector voltage of about half supply, a class A power amplifier will have a DC collector voltage approximately equal to the supply voltage (+12V in Fig. 5.2.2) and because of the transformer action, this allows a voltage swing of 12V above and below the DC collector voltage, making a maximum peak to peak signal voltage ( $V_{pp}$ ) available of 24V.

With no signal, the quiescent collector current of the (medium power) output transistor may typically be about 50mA. When a signal is applied, the collector current will vary substantially above and below this level.

Class A power amplifiers, using the relatively linear part of the transistors characteristics are less subject to distortion than other bias classes used in power amplifiers, and although their inferior efficiency improves when output transformers are used, the introduction of a transformer can itself produce additional distortion. This can be minimised by restricting amplitude of the signal so as to utilise less than the full power of the amplifier, but even under optimum conditions the efficiency of class A presents problems. With substantially less than 50% of the power consumed from the supply going into the signal power supplied to the loudspeaker, the wasted power is simply produced as heat, mainly in the output transistor(s).

In large high power amplifiers class A is not practical. For example an amplifier used to produce 200W to a large loudspeaker system would need a 400W amplifier producing at its most efficient, 200W of wasted heat that must be dissipated by very large transistors and even larger heat-sinks if overheating, and subsequent component failure is to be avoided. Class A output stages are therefore used mainly in low to medium power output stages of 1 to 2 watt and below, such as domestic radio or TV receivers and headphone amplifiers.



Module 5.3

# Class B Power Amplifiers

What you'll learn in Module 5.3

**After studying this section, you should be able to:**

Understand the operation of class B power amplifiers.

- Class B biasing.
- Push-pull operation

Understand crossover distortion.

- Causes and effects.

List advantages and disadvantages of class B amplifiers.

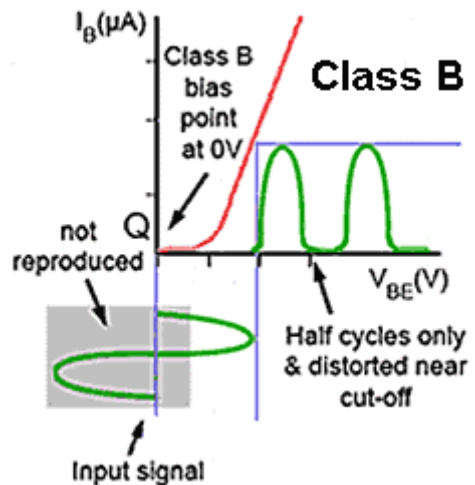


Fig 5.3.1 Class B Bias

## Class B

In amplifiers using class B bias, illustrated in Fig. 5.3.1, there is no standing bias current (the quiescent current is zero) and therefore the transistor conducts for only half of each cycle of the signal waveform. This dramatically increases efficiency, compared with class A. Theoretically nearly 80% efficiency can be achieved with this bias and in practical circuits, efficiencies of 50% to 60% are possible.

The downside for this increased efficiency is that the transistor only amplifies half the waveform, therefore producing severe distortion. However, if the other half of the waveform can be obtained in some other way without too much distortion, then class B amplifiers can be used to drive most types of output device. The aim is to obtain a good power gain with as much of the energy consumed from the power supply going into the load as possible. This should be as consistent with reasonable linearity (lack of distortion), as possible. Power output stages do however produce more distortion than do voltage or current amplifiers.

## RF Power Amplifiers Using Class B

The circuit in Fig 5.3.2 shows how class B bias can be used in a radio frequency (RF) output stage. Although the circuit would produce severe distortion as only half of the signal wave form produces a current in the load, because the load in this case is a [tuned circuit](#) resonating at the signal frequency, the resonating effect of the tuned circuit ‘fills in’ the missing half cycles. This method is only suitable at RF, as at lower frequencies the inductors and capacitors needed for the resonant circuit would be too large and costly for most applications. Because of the superior efficiency of class B it is a popular choice for power amplifiers, but to overcome the severe distortion caused by class B, audio amplifiers use a push-pull circuit.

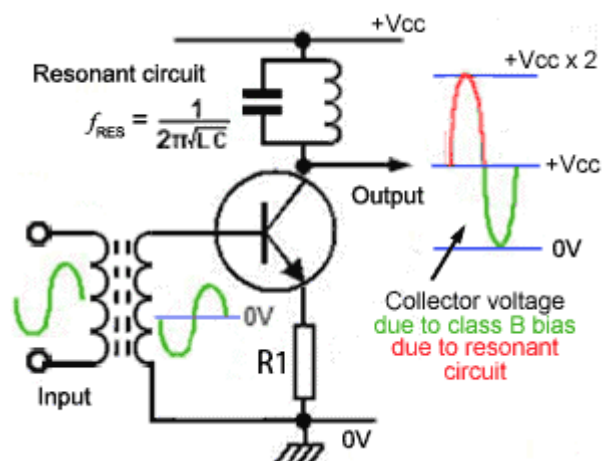


Fig 5.3.2 Class B Radio Frequency (RF) Power Amplifier

### Class B Push Pull Outputs

At lower (e.g. audio) frequencies, a common way to reduce the distortion due to the 'missing half cycle' in class B outputs, is to use a push-pull output stage. The principles of this circuit are shown in Fig. 5.3.3. Two identical but anti phase signals from a phase splitter are fed to the bases of a pair of power transistors so that each transistor (conducting only when the half cycle during which its input wave goes positive), feeds current to the load for that half cycle. The two half cycles are recombined in this circuit via a centre tapped transformer, which reverses the action of the phase splitter transformer, to produce a complete sine wave in the secondary.

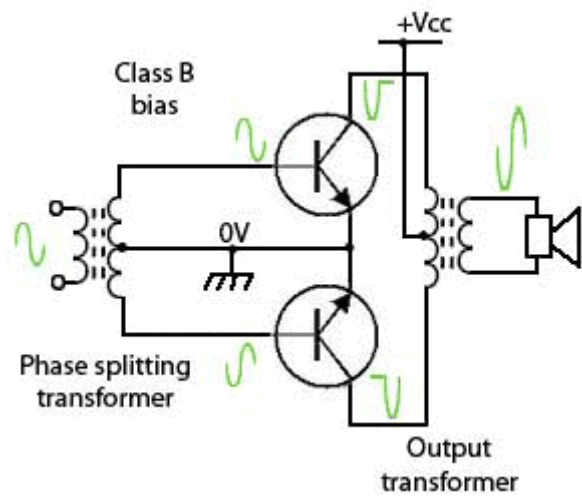


Fig 5.3.3 Class B Push-Pull Output

### Crossover Distortion

The main problem with class B push pull output stages is that each transistor conducts for NOT QUITE half a cycle. As shown in Fig. 5.3.4 distortion occurs on each cycle of the signal waveform as the input signal waveform passes through zero volts. Because the transistors have no base bias, they do not actually begin to conduct until their base/emitter voltage has risen to about 0.6V. As a result, there is a 'Dead Zone' of about 1.2V around the zero volts line (between -0.6V and +0.6V) where the signal waveform is not amplified, causing a "missing" section from the output signal, resulting in unwanted distortion during the "crossover" from one transistor to the other.

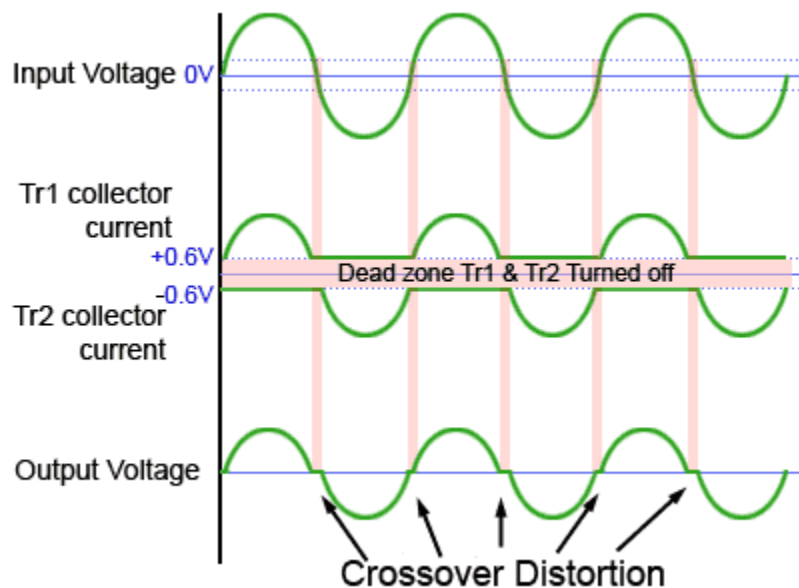


Fig 5.3.4 Crossover Distortion

The effect of this distortion on the output depends to some degree on the amplitude of the output signal, the larger the amplitude the less significant the missing 1.2 volts becomes. Also the distortion will be less severe at high frequencies where the rate of change of the wave, as it passes through zero is much faster, causing a shorter 'step' in the waveform.

The large and varying current drawn by a powerful class B amplifier also puts considerable extra demand on the DC power supply and as the current drawn varies with the amount of signal applied, the smoothing capabilities of the power supply must be efficient enough to prevent this varying current from creating voltage changes at audio frequencies on the power supply lines. If these are not adequately removed, unintended audio feedback into earlier amplifier stages can occur and cause problems with instability. This extra demand on power supply complexity adds to the cost of class B power amplifiers.

| Class B   |  |
|---|--|
| Advantages  | Disadvantages  |
| Very low standing bias current.<br>Negligible power consumption without signal. | Creates Crossover distortion.  |
| Can be used for much more powerful outputs than class A                         | Supply current changes with signal, stabilised supply may be needed. |
| More efficient than Class A.  | More distortion than Class A.  |

Crossover distortion is more of a problem in low and medium power class B amplifiers and the method used to eliminate it, is to use a class B amplifier that has some bias (and quiescent current) added so that the output transistors are conducting continually, and so avoiding the ‘dead zone’ of class B. As this method has some properties of both class A and class B it is called Class AB.

Module 5.4

# Push-pull Driver Circuits

What you'll learn in Module 5.4

**After studying this section, you should be able to:**

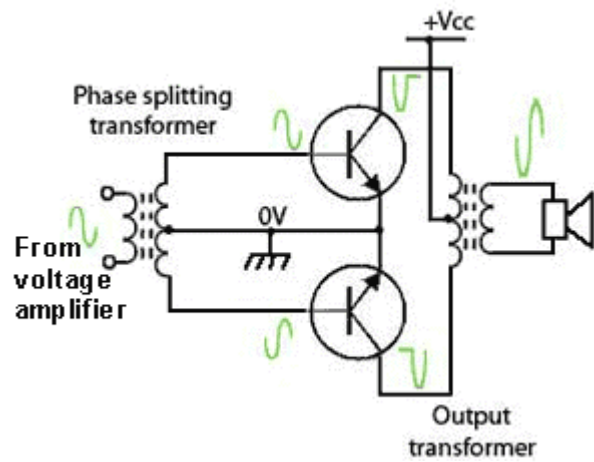
Understand the need for push-pull driver circuits.

- Driver transformers.

Understand the operation of transistor phase splitters.

- Phase splitter amplifiers.
- Emitter-coupled phase-splitter.

Know the principles of transformerless push-pull.



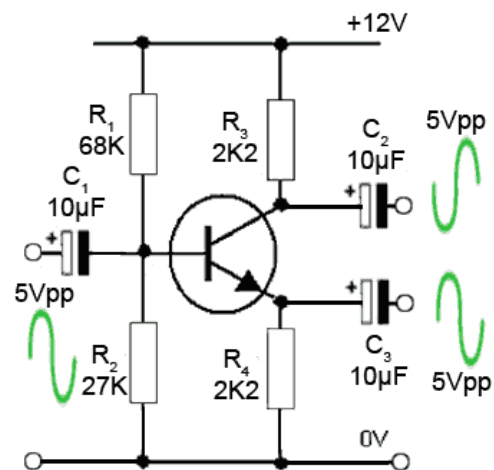
**Fig 5.4.1 Phase splitting using a driver transformer**

## Driver Transformer

When a pair of similar transistors (2 x NPN or 2 x PNP) is used in push-pull mode, it is necessary to supply their inputs with two identical anti-phase signals. This can be done by using a phase splitting transformer such as that shown in Fig. 5.4.1 to couple an audio voltage amplifier to the push-pull; output transistors. An output transformer with a centre tapped primary winding re-combines the two half cycles of the output waveform, so that the loudspeaker is fed with the complete waveform by the transformer secondary. The output transformer also provides impedance matching so that maximum power is delivered from the amplifier to the loudspeaker.

## Common Emitter Phase Splitter

An alternative method of providing anti-phase inputs is by using a transistor phase splitter stage (Fig. 5.4.2); this circuit is just like a standard class A voltage amplifier, except that two outputs are provided, with two equal value load resistors, one from the collector to supply and one from the emitter to ground. Notice that the emitter resistor is not decoupled, and therefore 100% negative feedback will be present, making the stage gain = 1. The maximum amplitude of the two output signals will each be slightly less than half the supply voltage (i.e. about 5Vpp each for a 12V supply). The purpose of this circuit is not to amplify, but simply to provide two equal and anti-phase signals.



**Fig 5.4.2 Phase splitting using a transistor amplifier**

### Emitter Coupled (Long Tailed pair) Phase Splitter

The phase splitter circuit illustrated in Fig. 5.4.3 is based on the emitter coupled, or long tailed pair differential amplifier, commonly found within integrated circuits. In this discrete component version the audio input is applied to the base of Tr1 while the base of Tr2 is held at a steady DC potential. No AC appears on the base of Tr2 due to the decoupling capacitor C3. Notice that both transistors share the same emitter resistor  $R_e$  and two anti phase outputs are taken from the two collectors.

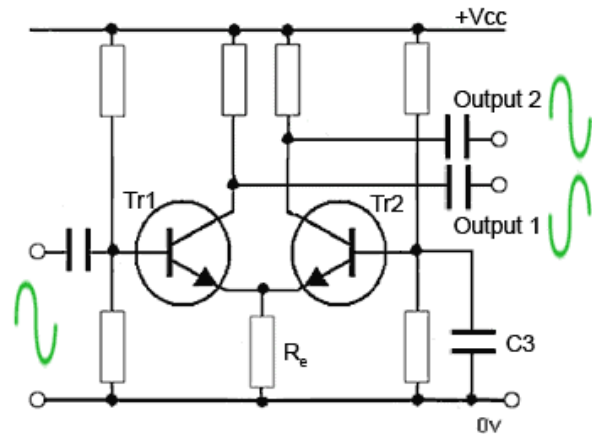


Fig 5.4.3 Emitter Coupled (Long Tailed pair)

### Operation

When the voltage at Tr1 base increases during the positive going half cycle of the input wave, the voltage at Tr1 collector will fall as the current through Tr1 increases. This increase in Tr1 current will tend to increase the voltage across the shared emitter resistor  $R_e$ .

This rise in emitter voltage will also be seen at Tr2 emitter, and as the base of Tr2 is held at a steady potential the base/emitter potential of Tr2 will be reducing, tending to turn Tr2 off. The consequent fall in current through Tr2 will cause its collector voltage to rise; note that this rise is in anti phase to the fall in Tr1 collector voltage. The two collectors are  $180^\circ$  out of phase, and this condition continues throughout the whole cycle of the audio signal.

Provided that the current gain and temperature stability of the two transistors are perfectly matched, the rise in emitter current due to one transistor turning on will be exactly matched by the fall in current due to the other transistor turning off. Therefore the voltage across  $R_e$  should remain constant and no AC signal will appear across  $R_e$ . In practice this is not easy to achieve in discrete (individual components) circuits due to the spread in characteristics in individual transistors during manufacture. In integrated circuit manufacture all the transistors in the chip are fabricated on the same piece of silicon, under exactly the same conditions, so it is much easier to match the two transistors. There are however, a number of [matched pair transistors](#) available in IC form containing just a pair of matched transistors.

### Transformerless Push-Pull

Another popular push pull amplifier design operates with neither a phase splitter input or an impedance matching output transformer. Instead it uses a complimentary pair of transistors, that is one NPN and one PNP transistor connected in common collector (emitter follower) mode as shown in Fig. 5.4.4.

An output transformer is not needed as the transistors in emitter follower mode have a low enough output impedance to match directly to output devices having a typical impedance of about 25 to 75 ohms, such as loudspeakers or motors. Because of the complimentary pair working in opposite polarity to each other (the NPN transistor biased on by the positive half cycle, while the PNP is biased off by the same half cycle), no phase splitting circuit is needed either.

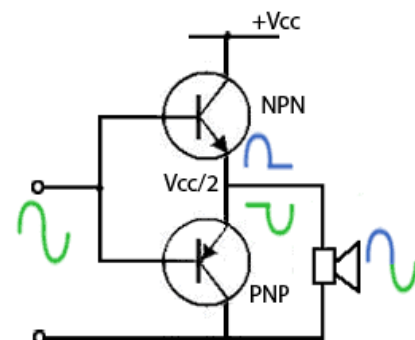


Fig 5.4.4 Transformerless push-pull operation using a complementary pair

## Module 5.5

## Class AB Power Amplifiers

What you'll learn in Module 5.5

**After studying this section, you should be able to:**

Understand Class AB amplifiers.

- Complementary operation.
- DC bias stabilisation.
- Temperature stabilisation.
- Mid-point adjustment.
- crossover adjustment.
- AC negative feedback.
- Bootstrapping.

Understand the need for Quasi AB amplifiers.

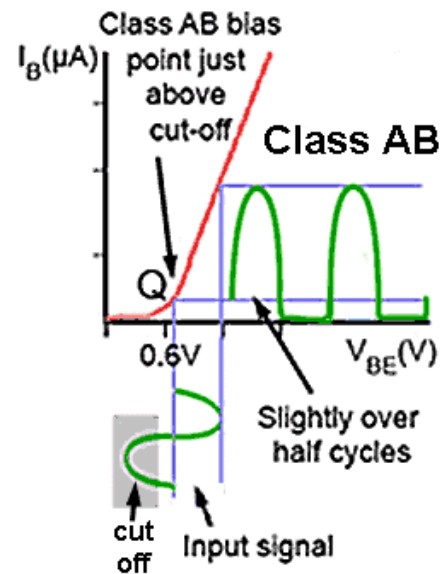


Fig 5.5.1 Class AB Bias

## Class AB Power Amplifiers

The class AB push-pull output circuit is slightly less efficient than class B because it uses a small quiescent current flowing, to bias the transistors just above cut off as shown in Fig. 5.5.1, but the crossover distortion created by the non-linear section of the transistor's input characteristic curve, near to cut off in class B is overcome. In class AB each of the push-pull transistors is conducting for slightly more than the half cycle of conduction in class B, but much less than the full cycle of conduction of class A.

As each cycle of the waveform crosses zero volts, both transistors are conducting momentarily and the bend in the characteristic of each one cancels out.

Another advantage of class AB is that, using a complementary matched pair of transistors in emitter follower mode, also gives cheaper construction. No phase splitter circuit is needed, as the opposite polarity of the NPN and PNP pair means that each transistor will conduct on opposite half cycles of the waveform. The low output impedance provided by the emitter follower connection also eliminates the need for an impedance matching output transformer.

Matching of current gain and temperature characteristics of complementary (NPN/PNP) transistors however, is more difficult than with just the single transistor type as used in class B operation. Also with no emitter resistors, due to the use of emitter follower mode, temperature stability is more difficult to maintain. Class AB therefore, can have a greater tendency towards thermal runaway.

Fig 5.5.2 illustrates the method of applying the class AB bias to a complementary pair of transistors. The two resistors R1 and R2 apply voltages to the output transistor bases so that Tr1 (NPN) base is about 0.6V more positive than its emitter, and Tr2 (PNP) base is about 0.6V more negative than its emitter, which is at half of  $V_{CC}$ .

To overcome crossover distortion, the bias on the base of each transistor needs to be accurately set so that the transistors will begin to conduct as soon as their respective half cycle begins, it is therefore common for R2 to be made adjustable.

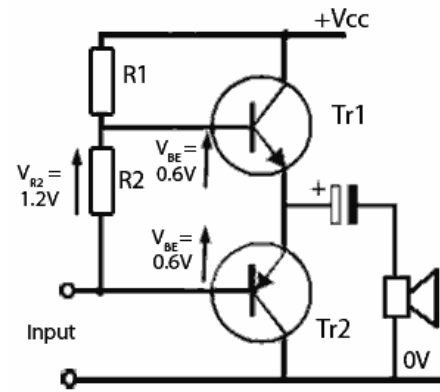


Fig 5.5.2 Applying Class AB Bias

Class AB Complementary Push Pull Output Stage

The output circuit shown in Fig 5.5.3 includes many of the features and techniques described throughout Amplifier Modules 1 to 5. It shows a class AB output stage (Tr2 and Tr3) and a class A audio driver (voltage amplifier) Tr1. The circuit features both AC negative feedback to reduce distortion and noise, and widen bandwidth, as well as DC negative feedback to stabilise the DC biasing. There is also some positive feedback, ‘Bootstrapping’ applied to increase input impedance and improve efficiency. Other essential features include the use of diodes to provide thermal stability, and some bias adjustments to give minimum distortion.

Operation

Tr1 driver transistor is a class A voltage amplifier fed with a variable amplitude audio signal from the input via the volume control VR1. Bias for Tr1 is provided via the potential divider R2, Vr2 & R3 from the junction of Tr2 & Tr3 emitters, which will be at half of the supply voltage.

DC Bias Stabilisation

Biasing for Tr2 and Tr3 is provided by the current flowing through the loudspeaker (which is also the output load for the amplifier), R5 and VR3. This provides an appropriate base current on Tr2 and Tr3 to make the emitters of Tr2 and Tr3 (the mid-point), half of the supply voltage. Because the base bias for Tr1 (via R2, VR2 and R3) is taken from the emitters of Tr2 and Tr3, if the voltage at the mid-point increases, the bias on Tr1 base will also increase, causing Tr1 to conduct more heavily.

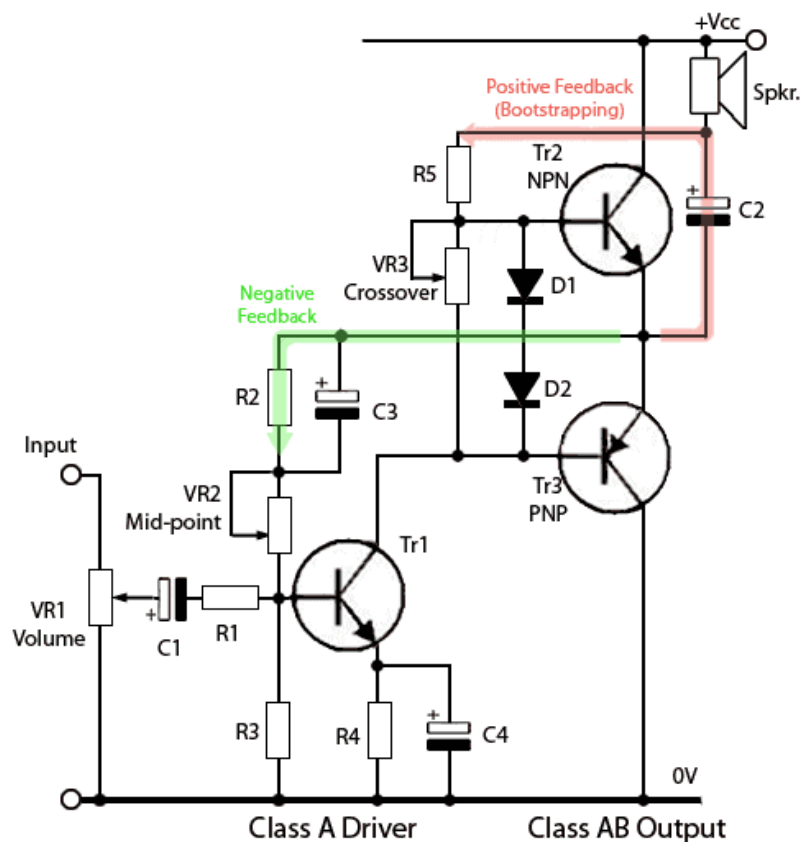


Fig 5.5.3 Class AB Output Stage

The collector voltage on Tr1 would therefore fall, also causing the voltages on the bases of Tr2 and Tr3 to fall. As Tr2 is NPN and Tr3 is PNP this would tend to turn Tr2 off and Tr3 on, reducing the voltage at the mid-point until it returns to its correct value of half supply.

If the voltage at the mid-point falls too far, this will result in a lowering of the bias voltage on Tr1, turning it off and increasing its collector voltage, and also the base voltages of Tr2 and Tr3. This action will increase the conduction in (NPN transistor) Tr2 and decrease conduction in (PNP transistor) Tr3, raising the mid-point to its correct voltage once more.

#### Temperature Compensation

D1 & D2 are two silicon diodes having a similar junction potential as Tr2 and Tr3. They are connected across the output transistors base/emitter junctions to improve thermal stability. As Tr2 and Tr3 warm up, their base/emitter junction potentials will naturally fall. This would lead to over biasing and more current flow in the transistors, leading eventually to thermal runaway. D1 & D2 are usually mounted on the same heat-sinks as the output transistors. Therefore as Tr2 and Tr3 heat up, so will D1 and D2.

The junction potential of the diodes also falls, and they begin to conduct. Because the voltage between the two output transistor bases is set by VR1 to 1.2V under cold conditions, D1 and D2 are initially just cut off. However if these diode junction potentials fall due to heating, they will begin to conduct and reduce to voltage between Tr1 and Tr2 bases. This will therefore reduce the bias on the output transistors and so maintain correct class AB bias conditions.

#### Mid-Point Adjustment

It is important that the mid-point voltage is kept accurately at half supply in order to obtain the maximum peak to peak output signal without clipping either peak of the waveform. VR2 is made variable so that the mid point voltage can be accurately set. This adjustment should only be needed after manufacture or when any components have been replaced. With no signal applied, a voltmeter connected to the mid point and VR2 is adjusted for half supply voltage.

#### Crossover Adjustment

VR3 is the 'Crossover Control' and it is adjusted with a sine wave signal applied to the amplifier input and observed on an oscilloscope connected across the output load, to give minimum crossover distortion. VR3 would be adjusted, either during manufacture or after component replacement, so that the voltage difference between the bases of Tr2 and Tr3 is such that a small standing (quiescent) current is flowing in to the bases of both Tr2 and Tr3. The voltage across VR3 will therefore be about  $0.6 \times 2 = 1.2V$ .

Because the effects of VR2 and VR3 interact with each other the adjustments would normally need to be repeated a number of times, each time with decreasing amounts of adjustment until both are correct, with the mid point voltage at half supply and crossover distortion minimised.

In commercial equipment, the correct method for adjusting VR2 and VR3 would normally be given in the manufacturers manual and these instructions should be followed precisely. The mid point and crossover controls are preset controls and once adjusted during manufacture should not normally be re-adjusted except where components have been replaced.

#### AC Negative Feedback

AC negative feedback is provided by C2 to increase bandwidth and especially to reduce distortion. This is important, as it is not possible to entirely eliminate crossover distortion by careful biasing alone.



### Bootstrapping

Tr2 & Tr3 are biased in class AB, and so must be biased just before cut off (i.e. with 0.6V between base and emitter). The bias resistor network for these transistors also forms the resistive load for Tr1. Therefore the value of R5 and VR3 is governed by the DC voltages required for correct base biasing of TR2 and Tr3.

To provide a high gain in the class A driver stage Tr1 the collector load should have as high a resistance as possible; this conflicts with the DC requirements for biasing Tr2 and Tr3. However the collector load resistor of Tr1 actually only needs to have a high resistance to AC signals; if a way can be found to give R5 and VR3 a high impedance at audio frequencies and yet retain an appropriate (much lower) resistance at DC the gain in the driver stage Tr1 can be increased.

To achieve this increase in gain, AC positive feedback (bootstrapping) is provided by C2, which feeds back the AC output signal to the top of R5. This AC signal is in phase with the signal on Tr2 and Tr3 bases, and positive feedback would normally cause oscillation, but this is prevented by the fact that Tr2 and Tr3 are operating in emitter follower mode and the voltage gain of an emitter follower is less than 1 (typically about 0.9).

This means that whatever the amplitude of the signal voltage is on Tr1 collector, about 0.9 of this signal appears at the top of R5, so the AC voltage developed across VR3 and R5 appears to be only one tenth of the signal on Tr1 collector, therefore the (AC) value of resistance of VR3 and R5 appears to be ten times higher than it actually is, giving a x10 increase in the gain of Tr1 without any change in the DC resistance of VR3 and R5.

### Quasi Class AB

Complementary output stages can be used effectively for power amplifiers, but as power increases above a few watts it becomes increasingly difficult to find PNP and NPN transistors with characteristics sufficiently closely matched to provide equal amplification of positive and negative half cycles. One solution is to use a Quasi-complementary output stage as illustrated in Fig. 5.5.4. In this circuit a low power complementary pair (Tr1 and Tr2) are used to drive a pair of High Power NPN output transistors (Tr3 and Tr4).

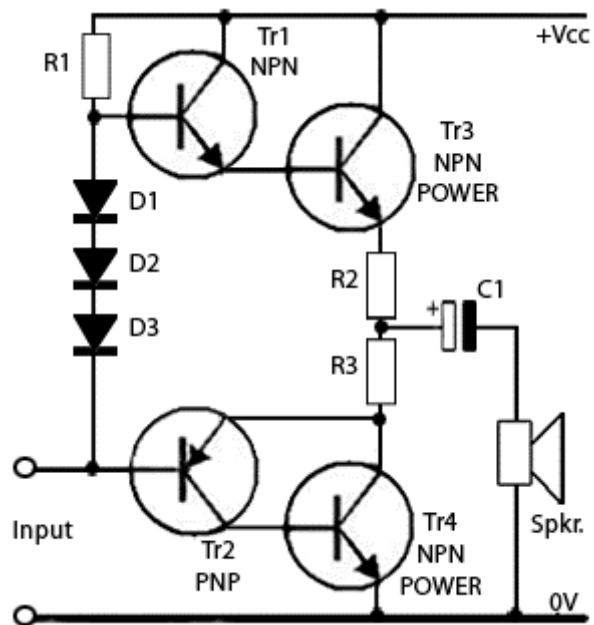


Fig 5.5.4 Quasi Class AB

## Module 5.6

## Amplifier Classes C to H

What you'll learn in Module 5.6

**After studying this section, you should be able to:**

Understand the differences between amplifier classes A to H:

- Class C bias.

Understand the operation of class D amplifiers & the need for:

- Pulse width modulation.
- Power switching.
- Output Filtering.

Understand the basic operation of classes E and F.

Understand the basic operation of classes G and H.

## Alternative Amplifier Classes

The class A Common Emitter Voltage Amplifier described in Amplifier Module 1, Module 2 and Module 3 has some excellent properties that make it useful for many amplification tasks, however it is not suitable for every purpose. Class A biasing is good at preserving the original wave shape as the transistor is biased using the most linear part of the transistor's characteristics. However the big problem with class A is its poor efficiency. Amplifiers Module 5.3 explains how push-pull class B power amplifiers improve efficiency at the expense of added crossover distortion.

Class AB power amplifiers, described in Module 5.5 largely address the problem of crossover distortion by combining elements of both class B and class A design but in doing so, again reduces efficiency. Although class AB is fine for what today would be considered low, or at best medium power amplifiers, the trend in recent years has been to make amplifiers more and more powerful, and where once 30W would have been considered quite adequate to fill a fairly large auditorium, it is now hardly enough for the car stereo! As a result, new classes of amplifier have been created to cope with this high power requirement.

## Class C Bias

In Class C, the bias point is placed well below cut-off as shown in Fig.5.6.1 and so the transistor is cut-off for most of the cycle of the wave. This gives much improved efficiency to the amplifier, but very heavy distortion of the output signal. Class C is therefore not suitable for audio amplifiers. It is however commonly used in high frequency sine wave oscillators and certain types of RF amplifiers, where the pulses of current produced at the amplifier output can be converted to complete sine waves of a particular frequency by the use of LCR resonant circuits.

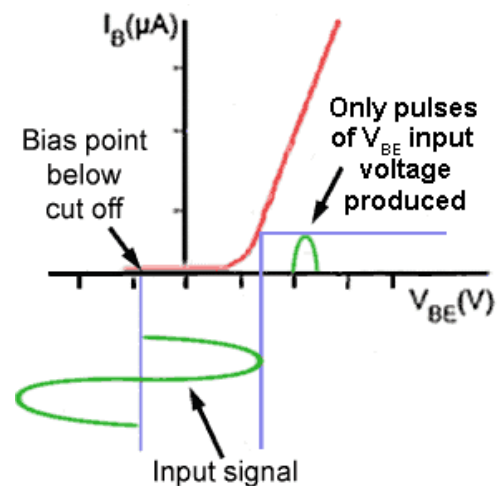


Fig. 5.6.1 Class C Bias

## Class D Amplifiers

In class D audio amplifiers, the basic operation of which is shown in Fig. 5.6.2, the audio signal is first converted to a type of digital signal called 'Pulse Width Modulation'. This is not a digital signal within the normally accepted definition of 'Digital' but only in that it has two levels, high and low. When such a signal is amplified, very little power is dissipated in the amplifier, resulting in much greater efficiency than in conventional analogue amplifiers. The PWM signal is finally converted back into analogue form at the output.

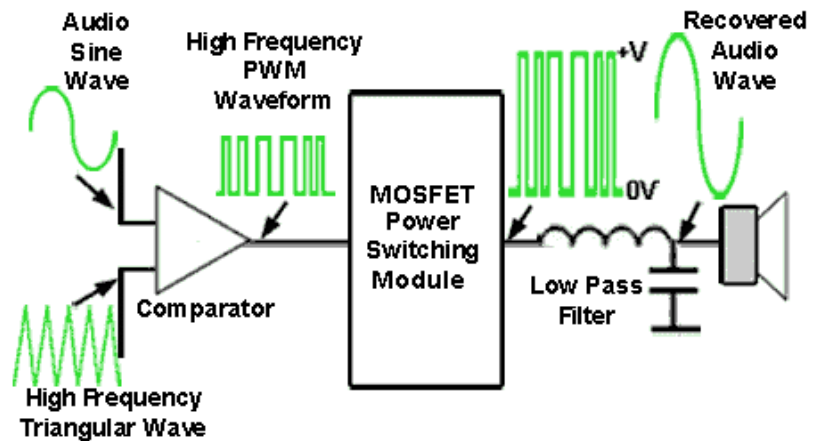


Fig. 5.6.2 Basic Principles of Class D

### Pulse Width Modulation

Fig. 5.6.3 illustrates how the audio signal is converted into a 'pulse width modulated' form using a comparator, which compares the audio signal, made up of relatively low frequency sine waves, with a much higher frequency triangular waveform. The output of the comparator switches to a high level if the instantaneous voltage of the triangular wave is higher than that of the audio wave, or to a low level if it is lower.

The comparator output therefore consists of a series of pulses whose widths vary in relation to the instantaneous voltage of the sine wave. The average level of the PWM signal has the same shape (though inverted in this case) as the original audio signal.

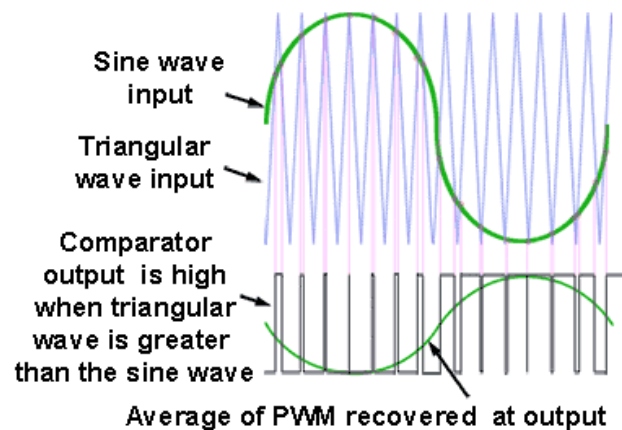


Fig. 5.6.3 Class D Operation

### Fast Power Switching

This PWM output then drives a switching circuit that uses fast switching MOSFET power transistors to switch the output between the full supply voltage (+V) and zero volts (0V). Representing the audio by a series of square pulses dramatically reduces power consumption. When the square wave is at its high level, the transistor is cut-off and although a high voltage is present, virtually no current is flowing, and as power is voltage x current, power is just about zero. During the time when the square wave signal is at its low level, there will be a large current flowing but the signal voltage is practically zero, so again, very little power dissipation. The only time when significant power is dissipated by the MOSFET transistors is during the change from high to low or low to high states. Because high speed switching MOSFETs are used, this period is extremely short, so average power dissipation is kept to a very low level.

## Output Filtering

Finally the high frequency, large amplitude PWM pulses are applied to a low pass filter, which removes the high frequency components of the waveform, leaving just the average level of the PWM wave, which because of the varying 'on' time of the pulses produces a large amplitude replica of the original sine wave audio input.

Class D operation makes the output circuit extremely efficient (around 90%) allowing high power output without the need for such high power transistors and elaborate heat-sinks. However this big increase in efficiency is only achieved at the expense of some increase in distortion and especially of noise, in the form of electromagnetic interference (EMI).

Because class D produces high frequency, large amplitude PWM 'square' waves at the output of the switching module, there will be many large amplitude odd harmonics present, which are a natural component of square waves. The frequencies of these harmonics can extend well into the radio frequency spectrum, and if not carefully controlled can cause radio interference radiated both directly, and conducted via the power supply.

As shown in Fig. 5.6.2 the PWM output is fed to the load via a low pass filter, which should remove the interference causing harmonics, however even with a good quality low pass filter all the harmonics causing interference cannot be removed from the square wave, as this would distort the square wave, and consequently the audio output.

Nevertheless, class D is a very efficient class of amplifier suited to both high power audio and RF amplifiers and low power portable amplifiers, where battery life can be considerably extended because of the amplifier's high efficiency. The increased interest in class D amplifiers has led to a number of class D integrated circuits becoming available, such as the 25 watts per channel stereo power amplifier TPA3120D2 from Texas Instruments and the 2 watts per channel digital input audio amplifier SSM2518 from Analogue Devices, suitable for mobile phones and portable mp3 players.

## Class E and F Power Amplifiers

Amplifier classes such as E and F are basically enhancements of class D, offering more complex and improved output filtering, including some additional wave shaping of the PWM signal to prevent audio distortion.

## Class G and H Power Amplifiers

Classes G and H offer enhancements to the basic class AB design. Class G uses multiple power supply rails of various voltages, rapidly switching to a higher voltage when the audio signal wave has a peak value that is a higher voltage than the level of supply voltage, and switching back to a lower supply voltage when the peak value of the audio signal reduces. By switching the supply voltage to a higher level only when the largest output signals are present and then switching back to a lower level, average power consumption, and therefore heat caused by wasted power is reduced.

Class H improves on class G by continually varying the supply voltage at any time where the audio signal exceeds a particular threshold level. The power supply voltage tracks the peak level of the signal to be only slightly higher than the instantaneous value of the audio wave, returning to its lower level once the signal peak value falls below the threshold level again.

Both classes G and H therefore require considerably more complex power supplies, which adds to the cost of implementing these features.

Power Amplifiers Module 5.7

# Power Amplifiers Quiz 5

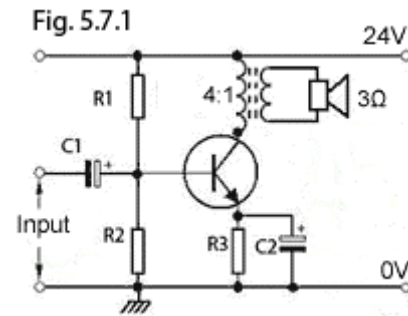
Try our quiz, based on the information you can find in Amplifiers Module 5. You can check your answers by going to:

<http://www.learnabout-electronics.org/Amplifiers/amplifiers57.php>

1.

Refer to Fig. 5.7.1: What will be the operating mode of the amplifier?

- a) Class A.
- b) Class B.
- c) Class C.
- d) Class D.



2.

Refer to Fig. 5.7.1: If the amplifier is delivering  $5W_{RMS}$  of audio power to the loudspeaker, what will be the approximate RMS voltage across the transformer primary?

- a) 3.9V      b) 5.1V      c) 11.4V      d) 15.5V

3.

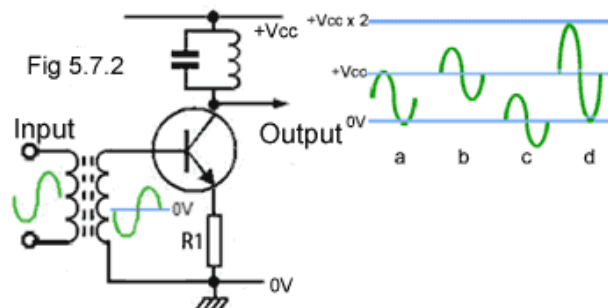
What is the main factor governing the maximum power rating ( $P_{TOT}$ ) of a transistor?

- a) The maximum collector voltage.
- b) The temperature of the base/emitter junction.
- c) The maximum collector current.
- d) The temperature of the base/collector junction.

4.

For the class B power amplifier circuit in Fig. 5.7.2, which of the output waveforms a b c d shows the correct output signal?

- a)
- b)
- c)
- d)



5.

Which of the following amplifier classes has a maximum theoretical efficiency of between 70 and 80%?

- a) Class A      b) Class AB      c) Class B      d) Class D

6.

Which of the following classes of amplifier is illustrated by the input characteristic shown in Fig. 5.7.3

- a) Class A.
- b) Class AB.
- c) Class B.
- d) Class C.

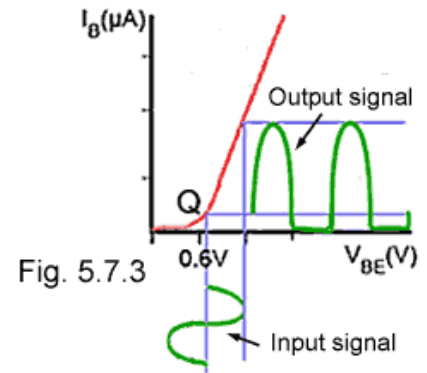


Fig. 5.7.3

7.

Refer to Fig. 5.7.4: What is the purpose of D1 and D2?

- a) To protect the base emitter junctions of Tr2 and Tr3 from reverse polarity.
- b) To prevent the wrong half cycles of the signal appearing at Tr2 and Tr3 bases.
- c) To provide temperature stabilisation for Tr2 and Tr3 bias.
- d) To eliminate crossover distortion.

8.

Refer to Fig. 5.7.4: What is the purpose of the capacitor C3?

- a) AC negative feedback.
- b) Bootstrap capacitor.
- c) Bass Boost.
- d) Mid point decoupling.

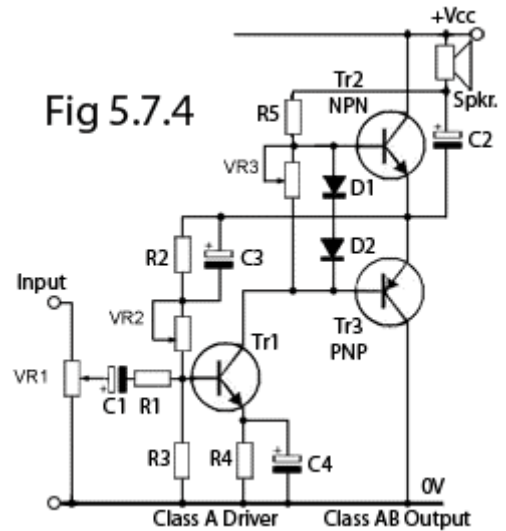


Fig 5.7.4

9.

Which of the stages listed below would drive the loudspeaker, in a class D amplifier?

- a) A comparator.
- b) A low pass filter.
- c) A pulse width demodulator.
- d) A MOSFET power switch.

10.

Which of the following problems may be expected as a result of using pulse width modulation (PWM) in audio amplifiers.

- a) PWM produces many even harmonics.
- b) PWM reduces the efficiency of the amplifier.
- c) PWM is more likely to produce RF interference.
- d) PWM output stages require excessively large heat sinks.