14

Analog Tutorial Lesson 14

Investigating Audio Power Amplifiers

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14.1 What You Will Learn

In this tutorial you will build and test common emitter and class AB amplifiers and compare their power efficiencies. Since small-signal approximation does not hold well for power amplifiers, you will use RF.Spice's Transient Test to analyze these nonlinear circuits.

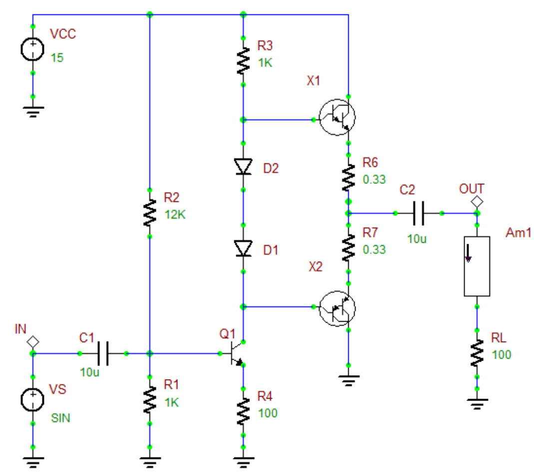
14.2 Exploring a Basic Common-Emitter Amplifier

The following is a list of parts needed for this project:

Part Name	Part Type	Part Value
VCC	Voltage Source	DC, 15 V
VS	Voltage Source	Waveform TBD
R1	Resistor	66 k
R2	Resistor	6 k
R3	Resistor	10 k
R4	Resistor	900
RL	Resistor	10 k
C1 - C2	Capacitor	1 u
C3	Capacitor	220 n
Q1	Q2N3904 NPN BJT	Defaults
Am1	Ammeter	N/A
IN, OUT	Voltage Probe Marker	N/A

Place and connect the parts of the basic common emitter amplifier as shown in the figure below:

Tutorial Project: Investigating Audio Power Amplifiers

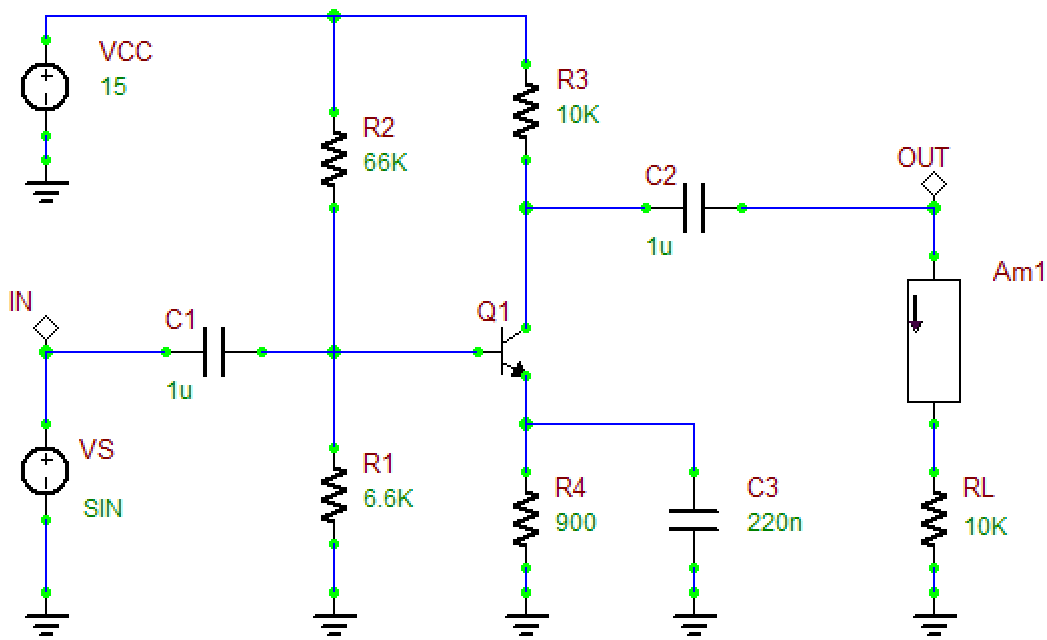


Objective: In this project, you will analyze several BJT amplifiers and examine their power efficiency and distortion characteristics.

Concepts/Features:

- Bipolar Junction Transistor
- Common Emitter Amplifier
- Class AB Amplifier
- Voltage Gain
- Load Current
- Power Efficiency
- Transient Test
- Darlington Pair
- Distortion Meter
- Total Harmonic Distortion

Minimum Version Required: All versions



The common-emitter amplifier.

Set the waveform of the voltage source VS according to the following table:

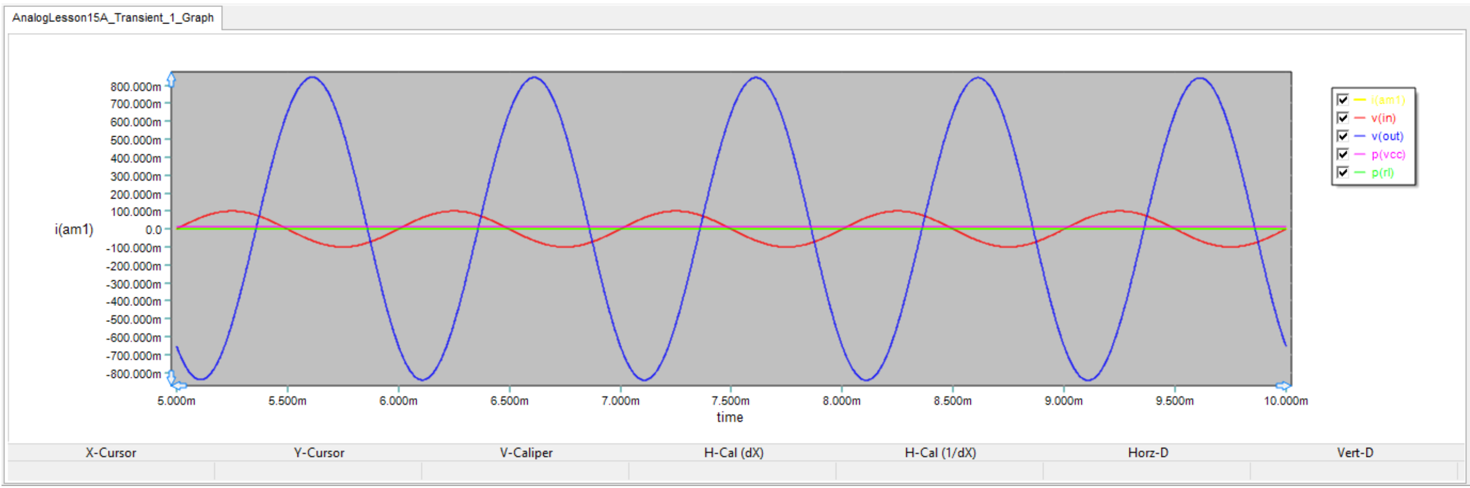
VS: Sinusoid

Offset Voltage	0
Peak Amplitude	100 mV
Frequency	1 kHz
Delay Time	0
Damping Factor	0

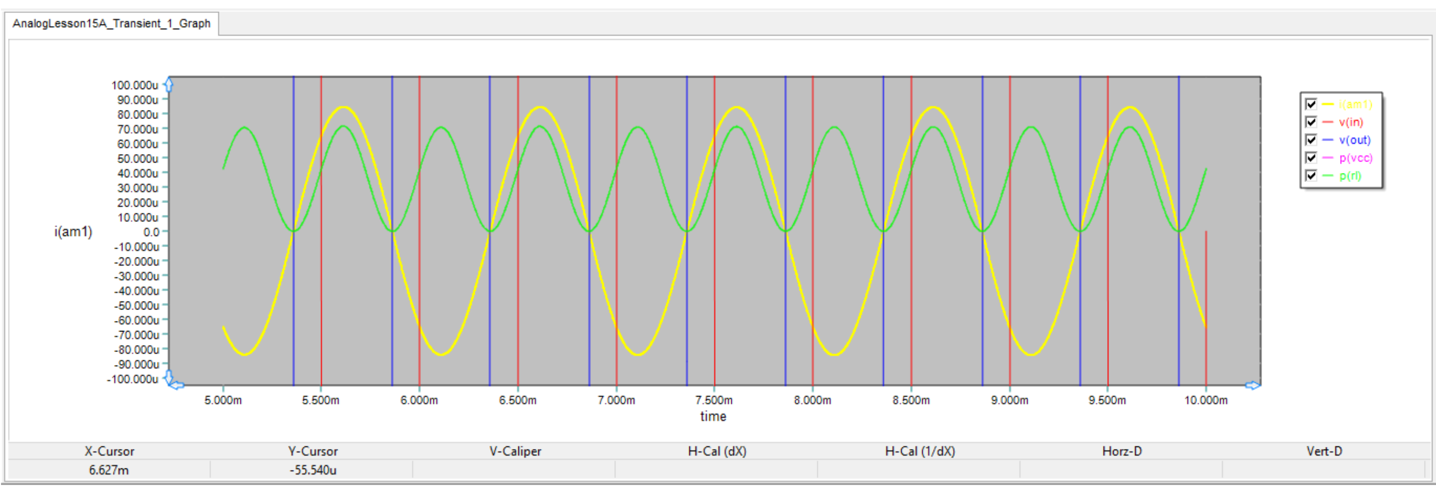
First, run a DC Bias Test of your amplifier to find the operating point parameters of Q1. You will find I_{CQ} = 755μA. Therefore, the small-signal transconductance of the transistor is $g_m = I_{CQ} / V_T$ = 0.029S. Run a Transient Test of this circuit with the parameters specified below:

Start Time	5 m
Stop Time	10 m
Linearize Step	10 u
Step Ceiling	1 u
Preset Graph Plots	v(in), v(out), i(rl), p(vcc), p(rl)

Note that the start time of the transient test in this tutorial is t = 5ms. Before you start to sample the waveforms, you need to let the transients settle down. The simulation results are shown in the figure below. Note that the five plots involve voltages, currents and powers with entirely different ranges and scales. Therefore, you need to use the "Zoom to Selected Plot" feature of the graph window to better view the details of each plot.



The joint graph of v(in), v(out), i(rl), p(vcc) and p(rl) in the common emitter amplifier circuit zoomed to v(out).



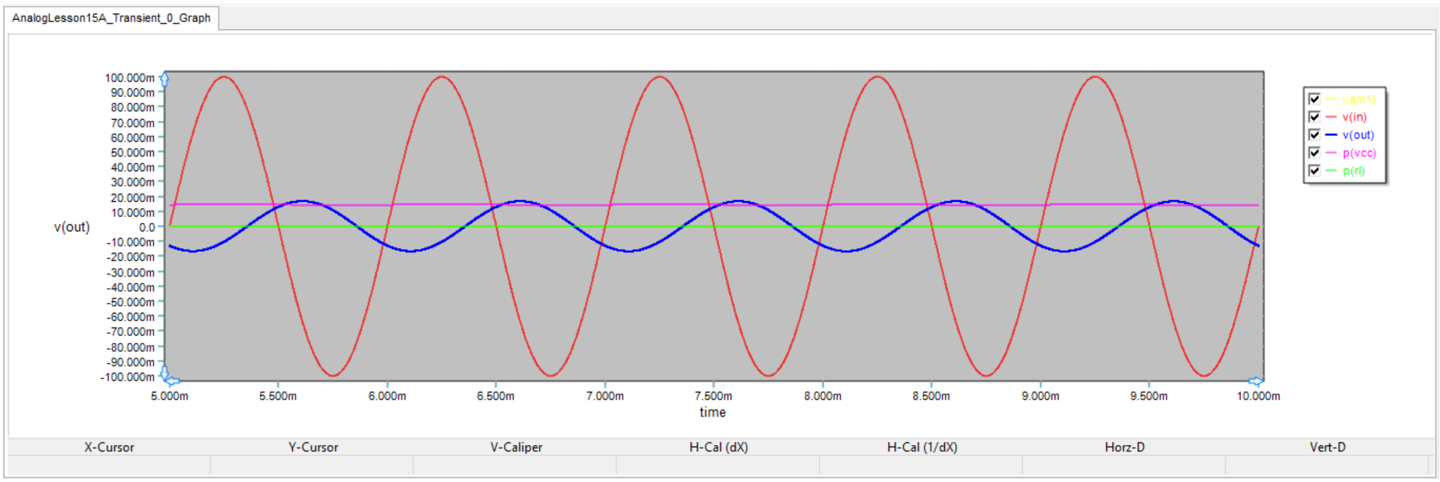
The joint graph of v(in), v(out), i(rl), p(vcc) and p(rl) in the common emitter amplifier circuit zoomed to i(rl) and p(rl).

In the above figure, p(vcc) is the DC power of the DC power supply VCC, while p(rl) is the power delivered to the load. The ratio p(rl)/p(vcc) defines the power efficiency of the amplifier. From the above plots, you can read the peak-to-peak input and output voltages, voltage gain and power efficiency:

RL	Vin(p-p)	Vout(p-p)	Voltage Gain	I_{RL}(p-p)	P_{VCC}	P_{RL}	Power Efficiency
10 kΩ	1686 mV	200 mV	8.43	168.5 μA	15.68 mW	71.28 μW	0.46%

14.3 Observing the Effect of Low Load Resistance

Audio power amplifiers are usually used to drive very small loads. Change the value of RL to 100Ω, and run the transient test once again. The results for a 100Ω load are shown in the figure and summarized below.

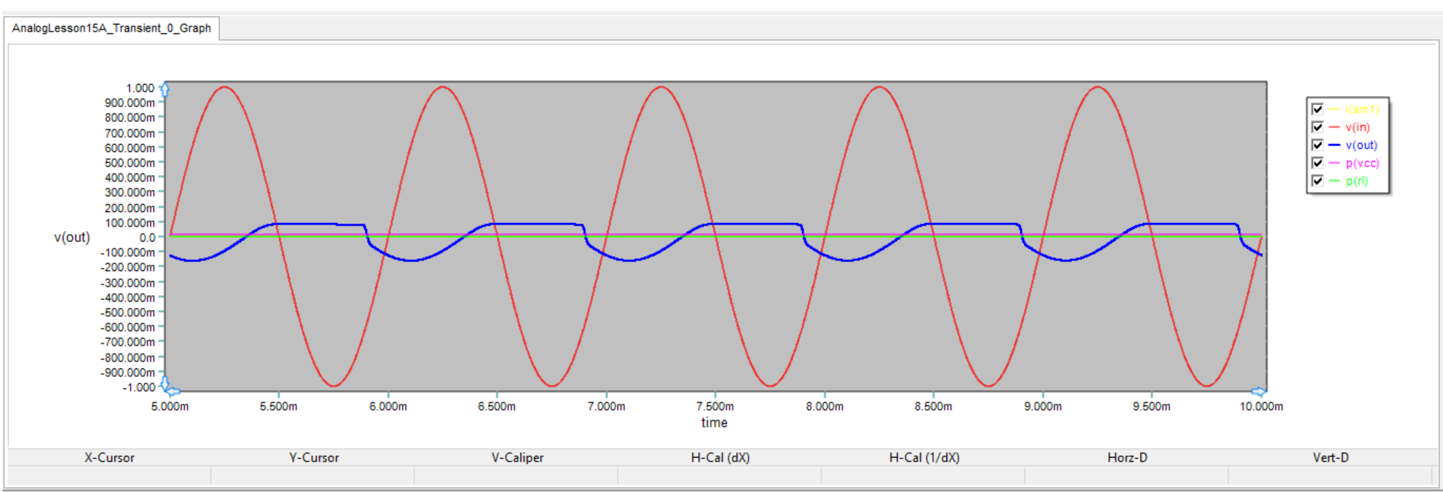


The joint graph of v(in) and v(out) in the common emitter amplifier circuit with RL = 100Ω.

RL	Vin(p-p)	Vout(p-p)	Voltage Gain	I_{RL}(p-p)	P_{VCC}	P_{RL}	Power Efficiency
100 Ω	34 mV	200 mV	0.17	167.4 μA	14.46 mW	2.8 μW	0.02%

You can see that the peak-to-peak output voltage has dropped drastically to 34mV. This is obviously expected since the 100Ω load shunts the collector resistor R3 and reduces the voltage gain: $G_V = -R_{C,tot} / R_{E,tot}$.

Finally, let's increase the input signal level from 100mV to 1V (2Vp-p) to see how the output is affected. The figure below shows the results:



Distorted output voltage due to large input voltage in the common emitter amplifier circuit.

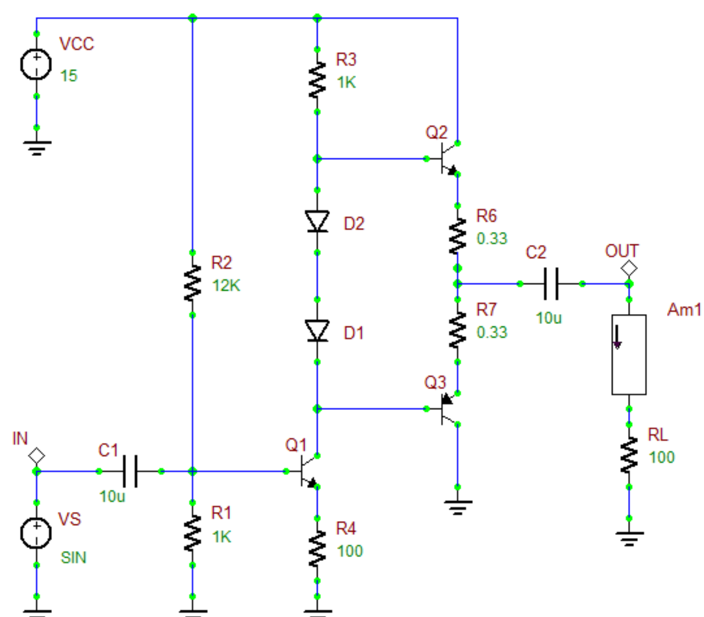
You can see that the load current has increased significantly to more than 1mA but at the expense of output voltage distortion. You may conclude that the common emitter amplifier is not an effective solution when the load is small.

14.4 Building and Testing a Class AB BJT Amplifier

The following is a list of parts needed for this part of the tutorial lesson:

Part Name	Part Type	Part Value
VCC	Voltage Source	DC, 15
VS	Voltage Source	Waveform TBD
R1	Resistor	1 k
R2	Resistor	12 k
R3	Resistor	1 k
R4	Resistor	100
R5 - R6	Resistor	0.33
RL	Resistor	100
C1 - C2	Capacitor	10u
D1 - D2	1N4148 Diode	Defaults
Q1 - Q2	Q2N3904 NPN BJT	Defaults
Q3	Q2N3906 PNP BJT	Defaults
Am1	Ammeter	N/A
IN, OUT	Voltage Probe Marker	N/A

Place and connect the part of the class AB BJT amplifier as shown figure below. The transistor Q1 acts as the driver amplifier. The complementary NPN-PNP pair Q2 and Q3 form the class AB amplifier, and the diodes D1 and D2 are used to bias them.



The class AB BJT amplifier with a driver stage.

Set the waveform of the voltage source VS according to the following table:

VS: Sinusoid

Offset Voltage	0
Peak Amplitude	500 mV
Frequency	1 kHz
Delay Time	0
Damping Factor	0

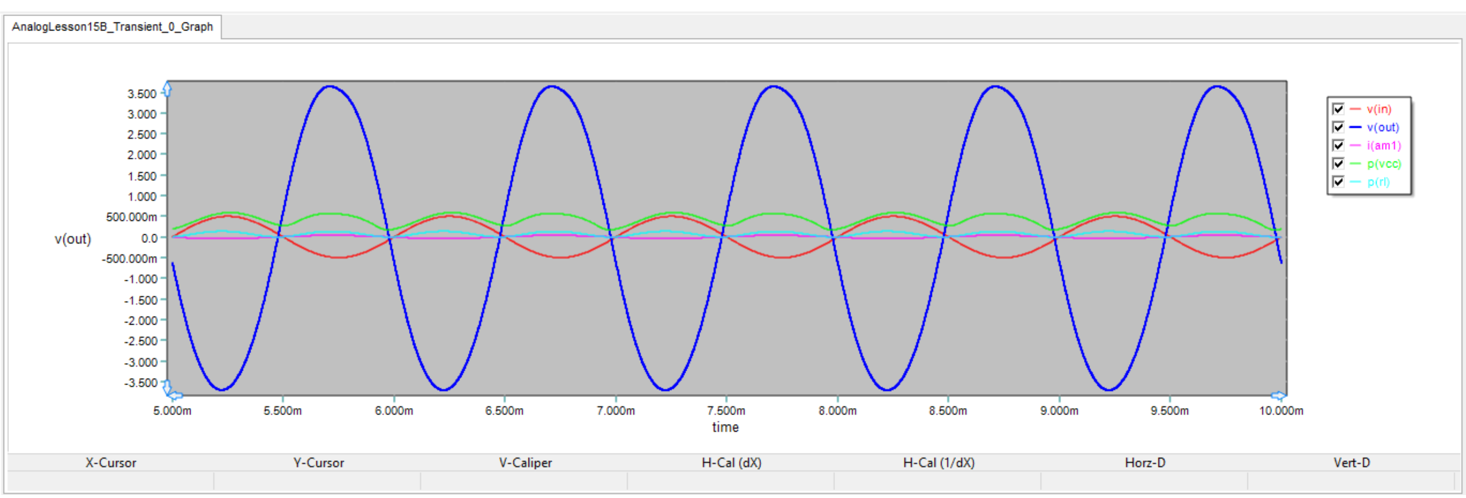
First, run a DC Bias Test of your amplifier to find the operating point parameters of the three transistors. The results are given below. As you would expect, the collector currents of Q2 and Q3 are almost equal in magnitude and have opposite signs.

I_{CQ1}	I_{CQ2}	I_{CQ3}
4.371 mA	9.995 mA	-9.983 mA

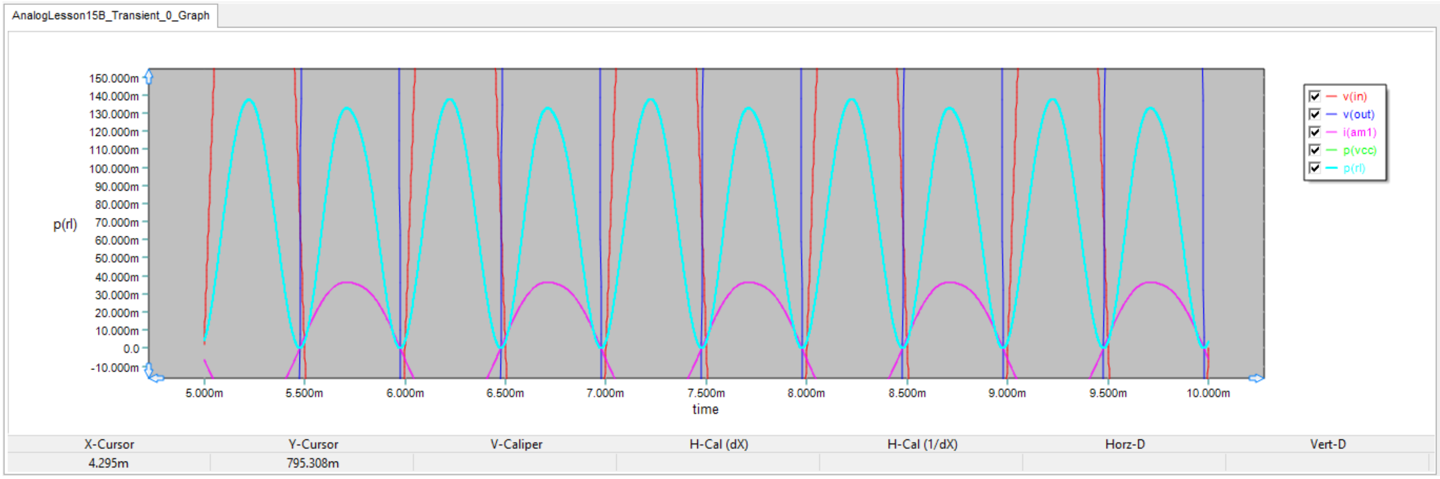
Run a Transient Test of this circuit with the parameters specified below:

Start Time	5 m
Stop Time	10 m
Linearize Step	10 u
Step Ceiling	1 u
Preset Graph Plots	v(in), v(out), i(rl), p(vcc), p(rl)

The results are shown in the figures below and summarized in the accompanying table. Note that the peak-to-peak output voltage is 7.36V without any serious distortion. The load peak-to-peak current is 73mA. In particular, the power efficiency is more than 23%, a significant improvement over the common emitter amplifier of the previous part.



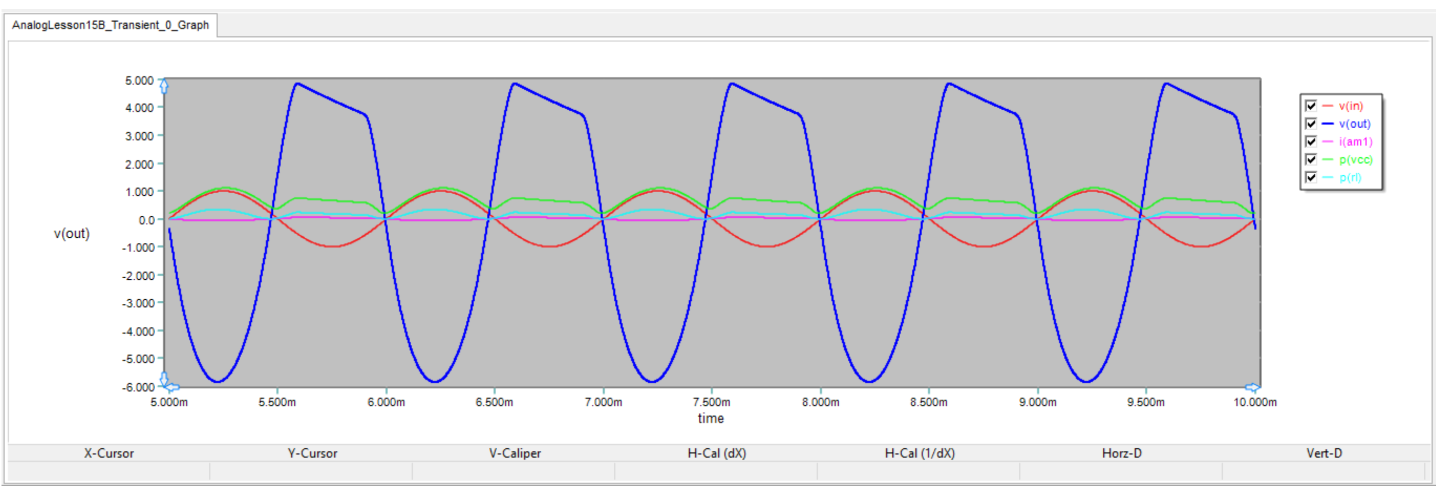
The joint graph of v(in), v(out), i(rl), p(vcc) and p(rl) in the class AB amplifier circuit zoomed to v(out).



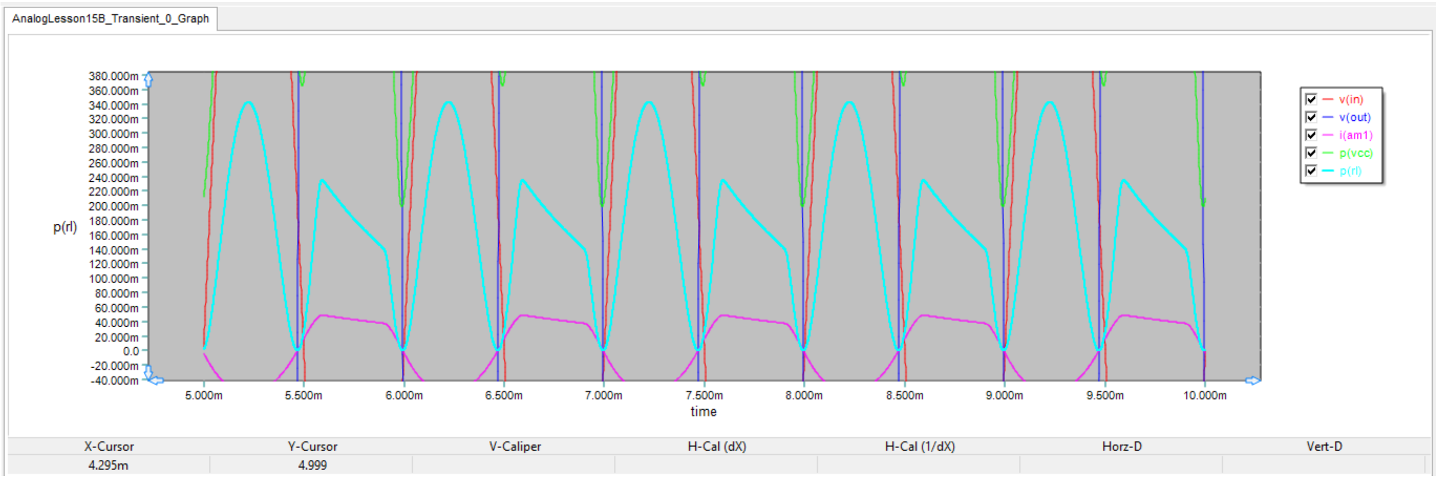
The joint graph of v(in), v(out), i(rl), p(vcc) and p(rl) in the class AB amplifier circuit zoomed to i(rl) and p(rl).

RL	Vin(p-p)	Vout(p-p)	Voltage Gain	I_{RL}(p-p)	P_{VCC}	P_{RL}	Power Efficiency
100 Ω	1000 mV	7356 mV	7.36	73 mA	590 mW	138 mW	23.4%

Similar to the previous part of this lesson, next increase the input signal level to 1V (2Vp-p) and run a new transient test with the same parameters. This time, both the output voltage and current are highly distorted as shown in the figures below:



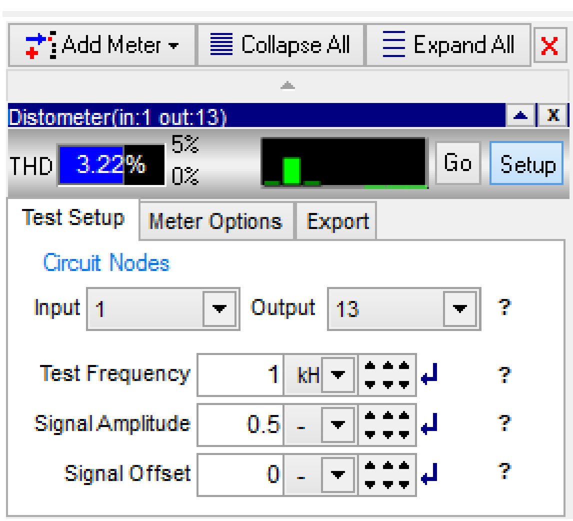
Distorted output voltage due to large input voltage in the class AB amplifier circuit.



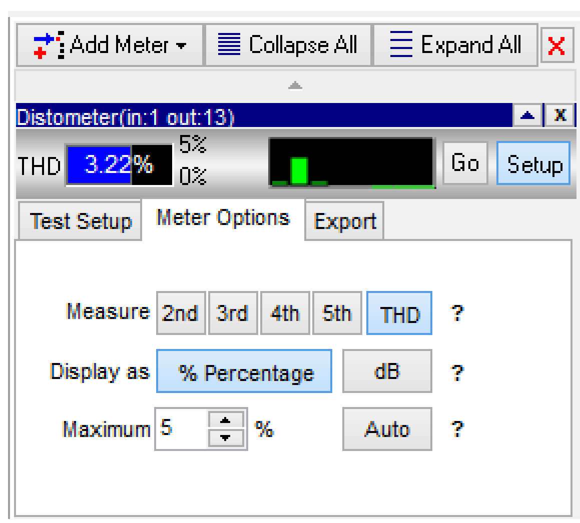
Distorted load current and output power due to large input voltage in the class AB amplifier circuit.

14.5 Distortion Analysis of the Class AB Amplifier

In Tutorial Lesson 2, you perform a "Fourier Analysis" of your circuit to characterize the spectral contents of signals. RF.Spice A/D also provides a convenient virtual instrument called **Distortion Meter** for this purpose. The distortion meter is particularly useful for the study of power amplifiers. To initiate a distortion meter, click the **Add Meter** button at the top of the "Virtual Instrument Panel" on the right side of the screen. From the drop-down menu, select **Distortion Meter**. Click the **Setup** button to open the property dialog of the instrument. It has three tabs. In the first tab labeled "Test Setup" set the circuits nodes 1 and 13 for input and output, respectively. Set the **Test Frequency** to 1kHz and **Signal Amplitude** to 0.5V, which is the peak amplitude of your source signal. Press the **Go** button. A harmonic analysis is performed, and the results are shown in the small black display of the instrument. A **Total Harmonic Distortion** (THD) of 3.22% is reported on the panel.



The Test Setup tab of the Distortion Meter instrument panel.



The Meter Options tab of the Distortion Meter instrument panel.

You can see from the bar chart that your class AB BJT amplifier only has a third harmonic component at VS = 0.5V. In the second tab of the panel, you can select individual harmonics and measure their distortion as given in the table below:

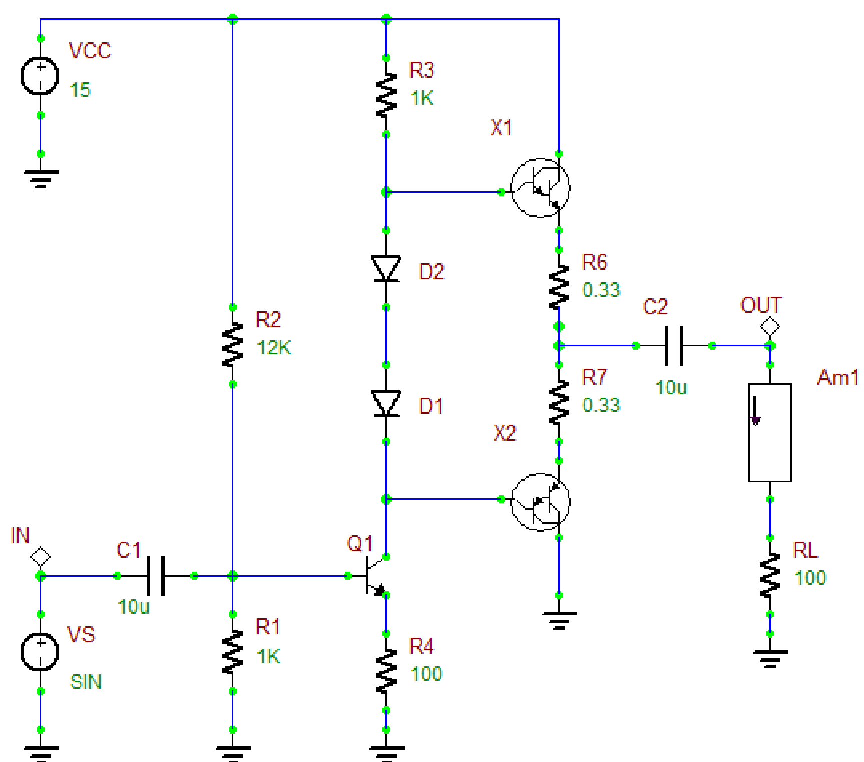
2nd Harmonic Distortion	3rd Harmonic Distortion	4th Harmonic Distortion	5th Harmonic Distortion	Total Harmonic Distortion (THD)
0.537%	3.11%	0.62%	0.128%	3.22%

14.6 Exploring the Use of Darlington Pairs

The following is a list of the additional parts needed for this part of the tutorial lesson:

Part Name	Part Type	Part Value
X1	TIP141 NPN Darlington BJT Pair	Defaults
X2	TIP147 PNP Darlington BJT Pair	Defaults

In this part of the tutorial lesson, you will replace the complementary BJT pair Q2 and Q3 with complementary NPN and PNP Darlington pairs. The NPN X1 pair will replace Q2 and the PNP X2 pair will replace Q3 in the circuit of the previous part. Everything else will remain the same.



The class AB BJT amplifier with complementary Darlington pairs and a driver stage.

Set the waveform of the voltage source VS according to the following table:

VS: Sinusoid

Offset Voltage	0
Peak Amplitude	500 mV
Frequency	1 kHz
Delay Time	0
Damping Factor	0

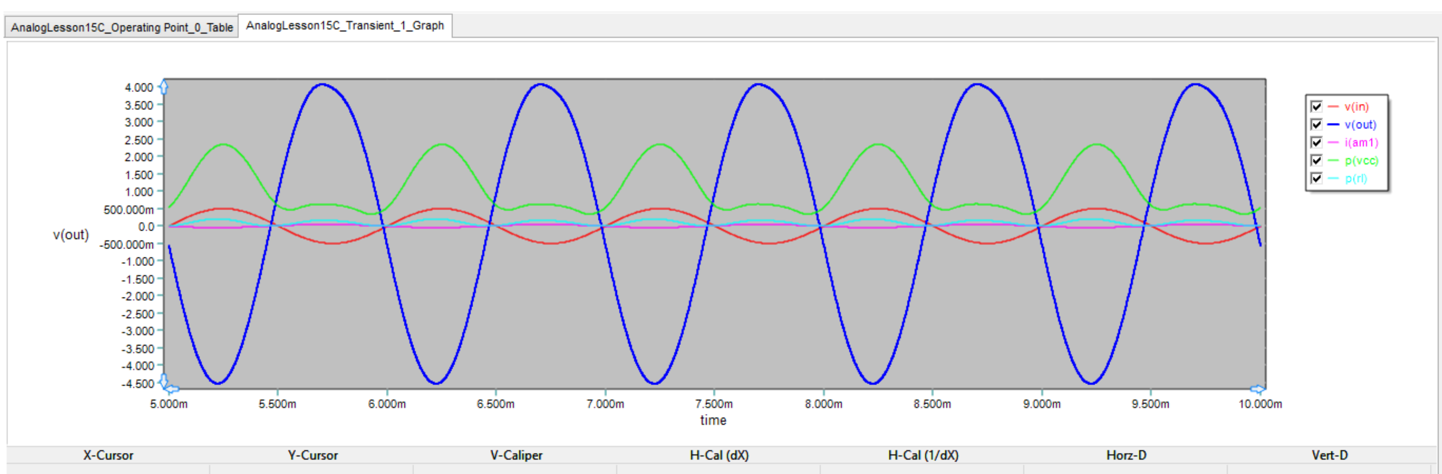
First, run a DC Bias Test of your amplifier to find the operating point parameters of the three transistors. The results are given below. As you would expect, the collector currents of Q2 and Q3 are almost equal in magnitude and have opposite signs.

I_{CQ1}	I_{CQ2}	I_{CQ3}
4.366 mA	31.756 mA	31.756 mA

Run a Transient Test of this circuit with the parameters specified below:

Start Time	5 m
Stop Time	10 m
Linearize Step	10 u
Step Ceiling	1 u
Preset Graph Plots	v(in), v(out), i(rl), p(vcc), p(rl)

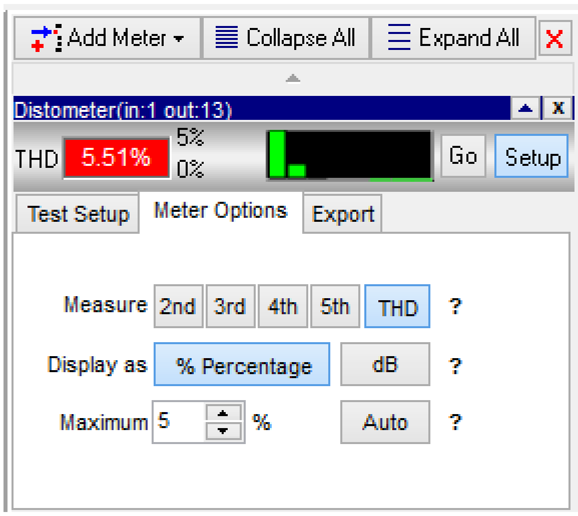
The results are shown in the figure and table below. You can see that both the load voltage and load current have increased in this case, which means a higher load power. In fact, the power delivered to the 100Ω load has increased by almost 50% over the previous case to more than 200mW. However, the power efficiency of the power amplifier has dropped to below 10%.



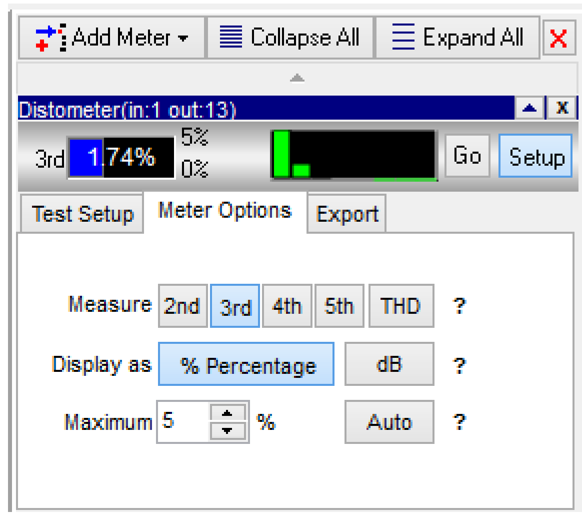
The joint graph of v(in), v(out), i(rl), p(vcc) and p(rl) in the class AB amplifier circuit with complementary Darlington pairs.

RL	Vin(p-p)	Vout(p-p)	Voltage Gain	I_{RL}(p-p)	P_{VCC}	P_{RL}	Power Efficiency
100 Ω	1000 mV	8.6 V	86 mA	167.4 µA	2.346 W	205 mW	8.7%

In the last part of this tutorial lesson, let's measure the distortion performance of your Darlington pair class AB amplifier. Follow the same procedure described above. The results are shown in the figures below:



The Test Setup tab of the Distortion Meter measuring a Darlington pair class AB amplifier.



The Meter Options tab of the Distortion Meter measuring a Darlington pair class AB amplifier.

Note that your Darlington pairs have introduced a significant second harmonic distortion, while the third harmonic distortion has decreased by half.

2nd Harmonic Distortion	3rd Harmonic Distortion	4th Harmonic Distortion	5th Harmonic Distortion	Total Harmonic Distortion (THD)
5.2%	1.74%	0.454%	0.22%	5.51%