Project -2

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Project Overview

Objectives:

- Harmonic Balance Simulations

You will learn:

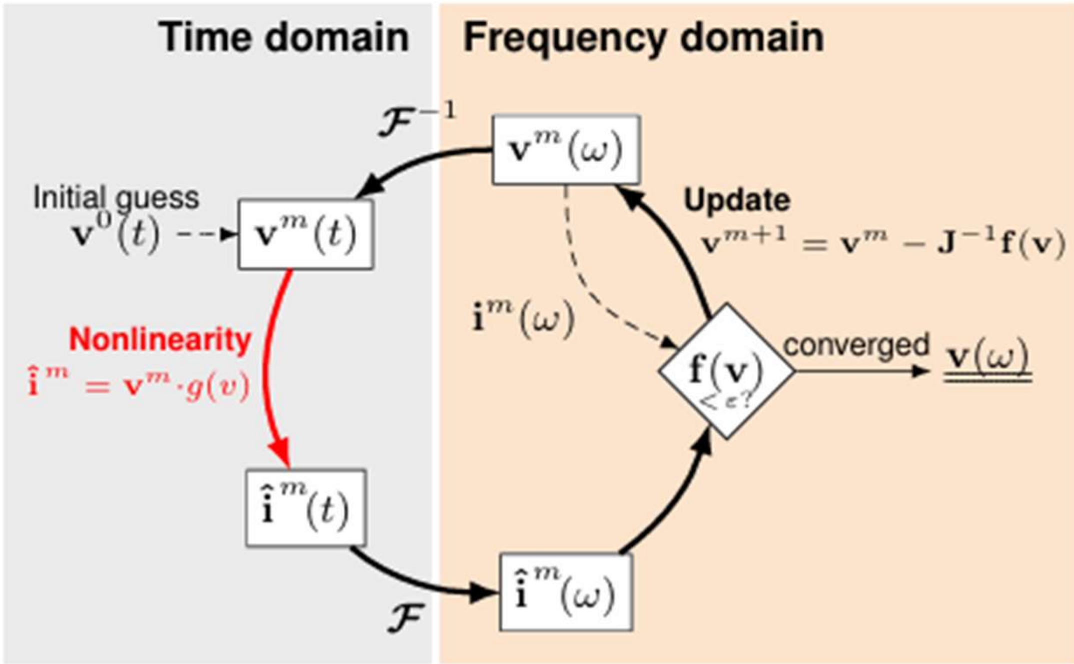
- Understanding the workings of Harmonic Balance
- Simulation Setup
- 1-dB Compression point (P-1dB)
- Third order intercept point (IIP3)
- Intermodulation Products (IM)

Task -1: Harmonic Balance

What are we learning?

In this section we will learn the concept of harmonic balance.

- How does it work?
- How do we simulate it?
- How do we estimate amplifier saturation, observe the output spectrum, and observe the non-linear components?



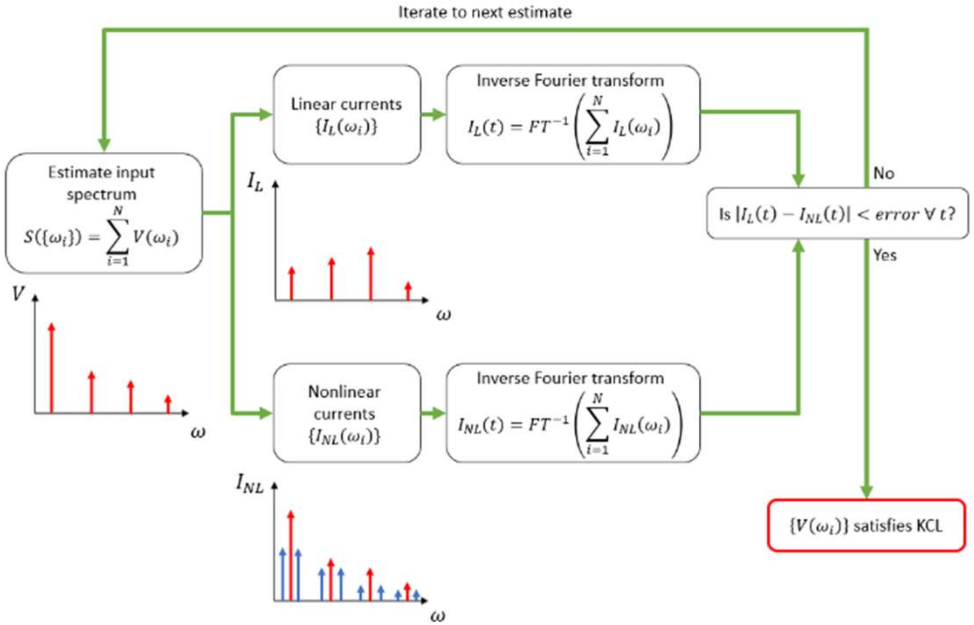
* Image cadence PCB

Task -1: Harmonic Balance Intro

Introduction:

Harmonic balance is a modeling technique that is used to estimate the steady-state response of a non-linear electrical system in the frequency domain.

- The name Harmonic Balance refers to the balancing of current obtained in the time domain and the currents obtained in the frequency domain.
- The figure represents the idea behind the Harmonic Balance algorithm.



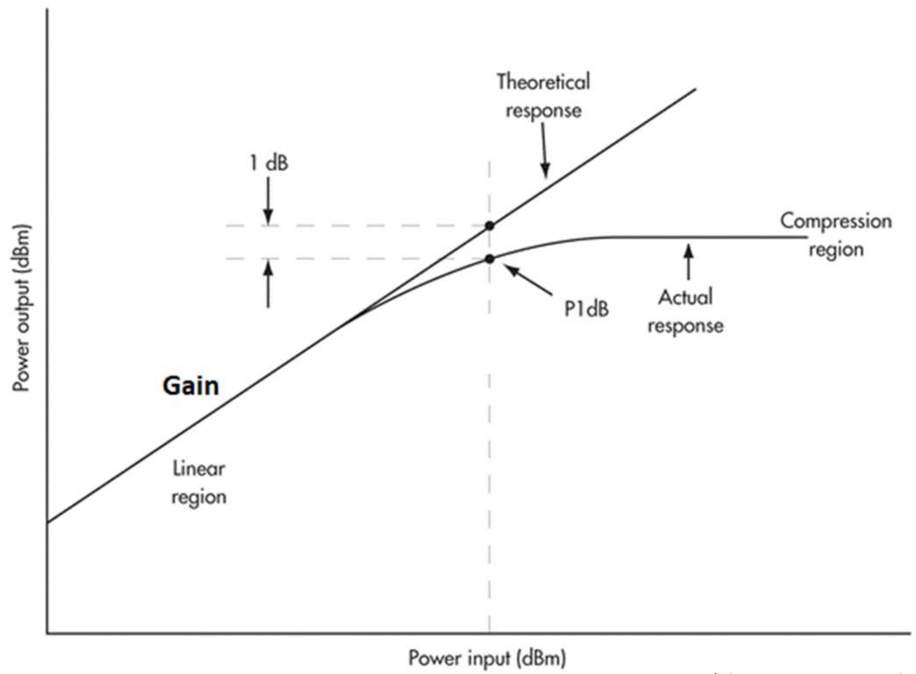
* Image cadence PCB

Task -1: Harmonic Balance 1-dB Compression

Introduction:

The 1 dB compression point (P1dB) is the output power level at which the **gain decreases 1 dB** from its low-powr (constant) gain value. Once an amplifier reaches its P1dB point, it goes into “compression” and exhibits a non-linear gain curve. This nonlinearity will produce distortion, harmonics and intermodulation products. Amplifiers are usually operated below the 1dB compression point.

- The curved line represents the non-linear response of the amplifier.
- The straight line is the theoretical response of the amplifier.
- The input power at the ‘1-dB’ deviation from the trend line is the input compression point.

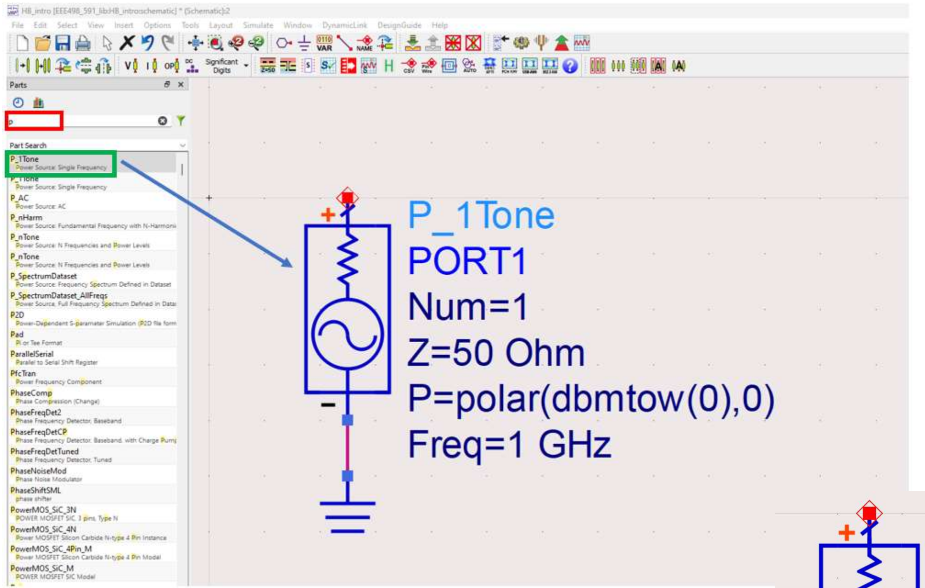


* Image courtesy Analog Devices

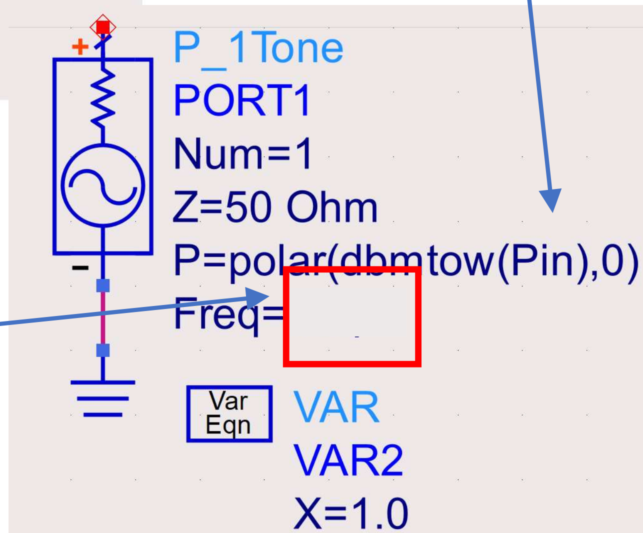
Task -1: Harmonic Balance Simulation

Working with the tool:

- In the palette window, search for "**P-1Tone**".
- Connect the ground terminal.
- Similarly search for **"var"**.
- Place the variable component in the schematic window.



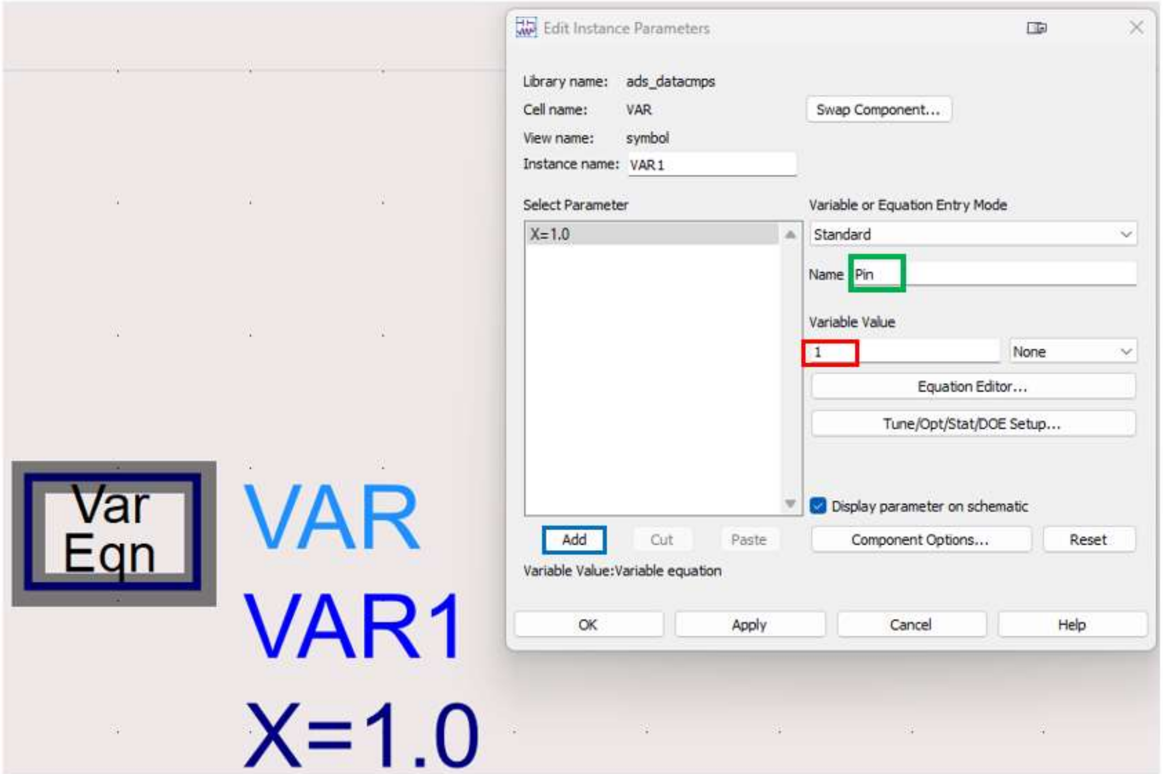
Set this power to "Pin", which will be a variable.



Create a variable name for the tone frequency.
This example uses "RF_freq" in the next slides.

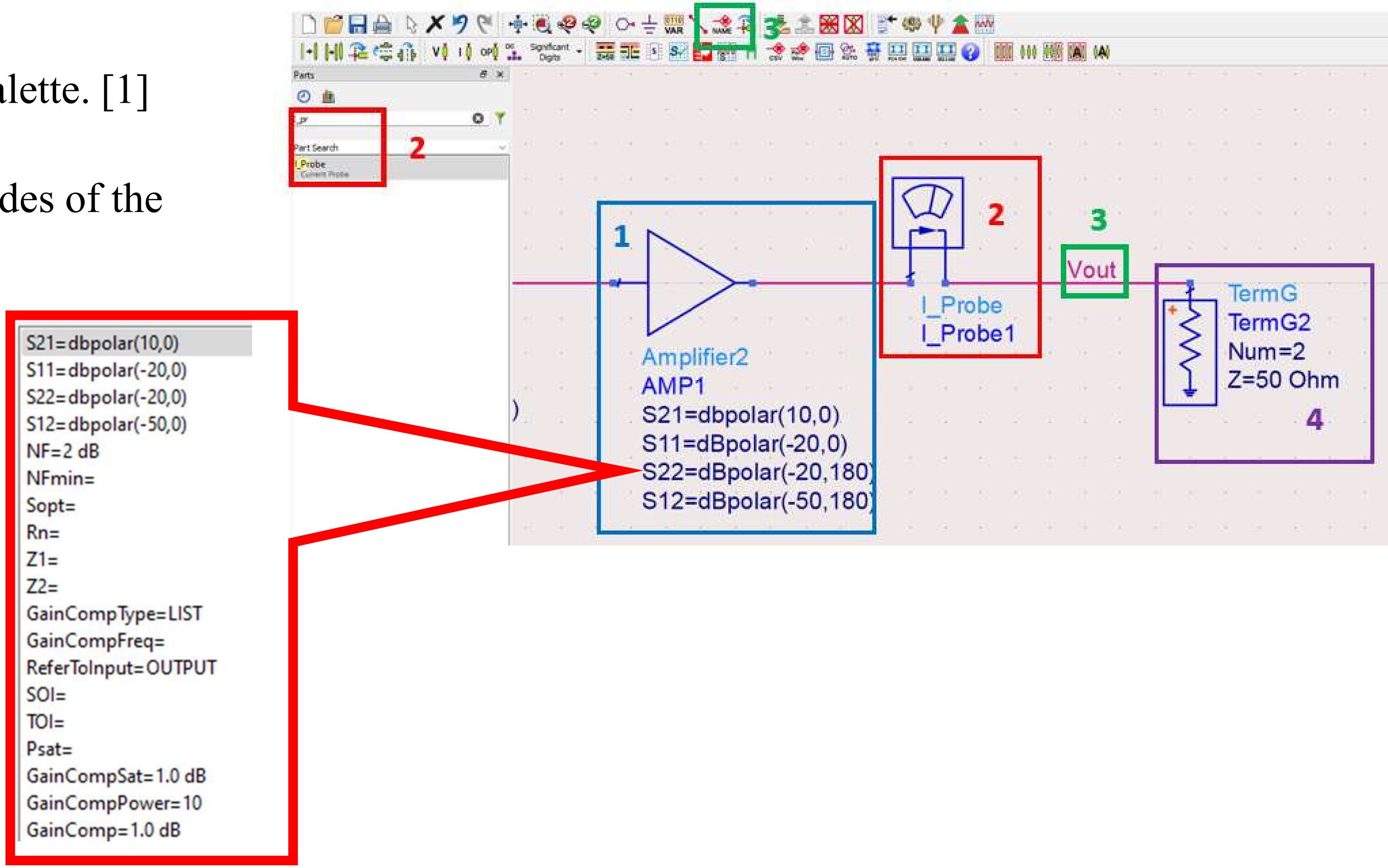
Task -1: Harmonic Balance

- Double click on the variable component.
- The parameter menu pops up, specify the variable name and set the appropriate value.



Task -1: Harmonic Balance

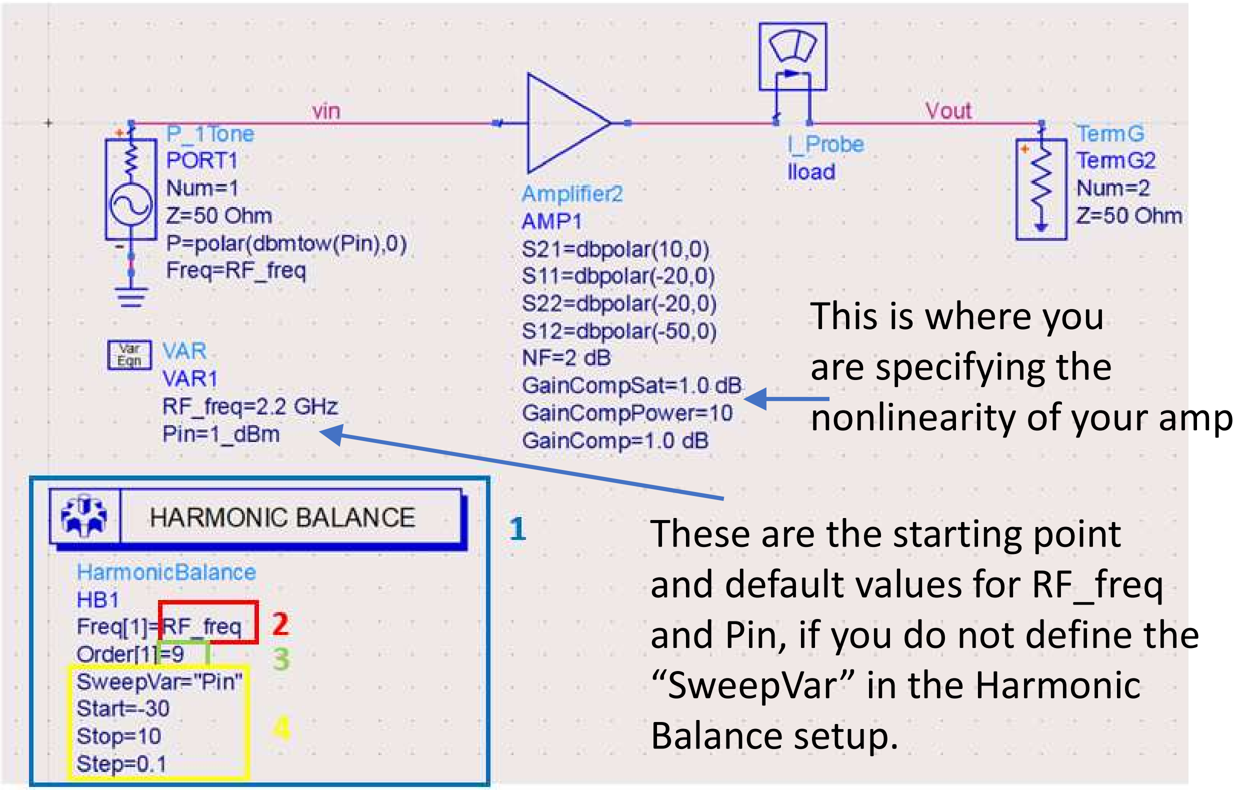
- Place an amplifier from the palette. [1]
- Place a Current probe [2]
- Name the input and output nodes of the circuit. [3]
- Place the termination port. [4]
- Set the variables as shown.
- After setting the value, select display parameter.



- **See next slide for the full schematic block diagram.**

Task -1: Harmonic Balance

- Place the harmonic balance simulation block from the component pallet. [1]
- Set the frequency component in the harmonic balance block to the variable you have defined. [2]
- Set the mixing order to 9 [3]
- Enable Sweep variable, start, stop and step. [4]
- Fill in the power variable you have defined as the sweep variable in double quotes. [4]
- Change the name of the probe to Iload (This will be needed for a later step)

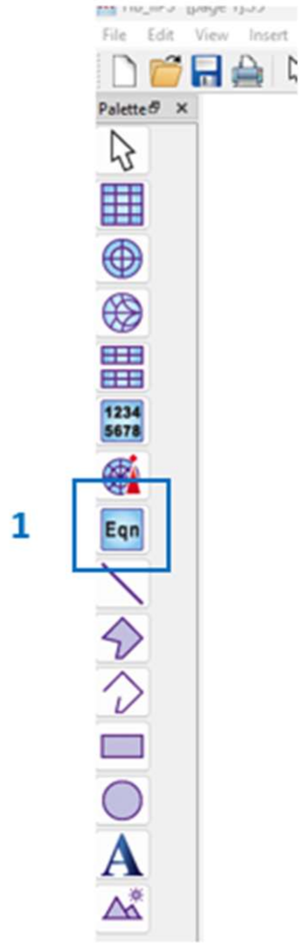


Task -1: Harmonic Balance

- After running the simulation, in the DDS (Graph) window please key in these equations.
- Select the equation Eqn component, as shown. [1]
- To better understand the mixing products (equations) **please refer to the appendix.**

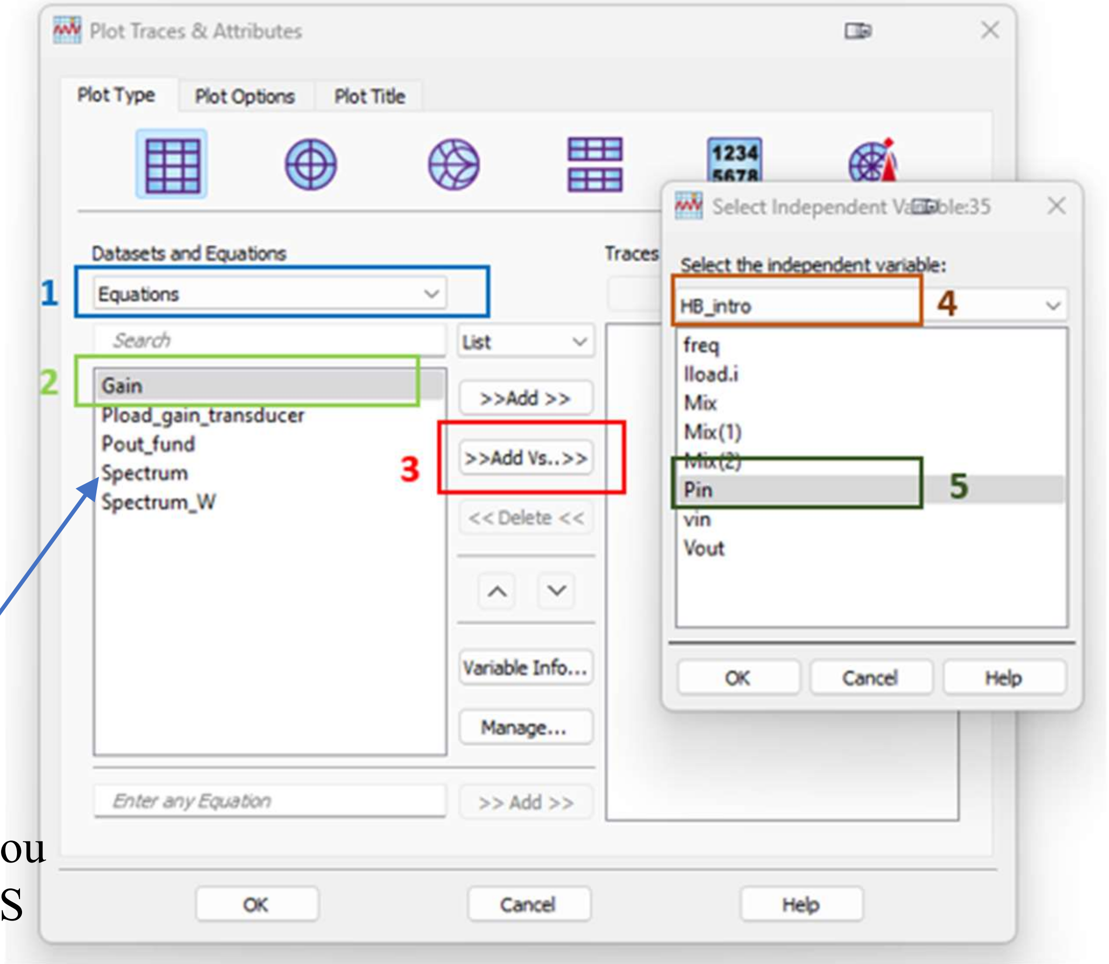
- In ADS, we create equations to plot various RF parameters, such as fundamental output power, gain, etc.

```
Eqn Spectrum_W=0.5*real(Vout*conj(Iload.i))
Eqn Spectrum=10*log(Spectrum_W)+30
Eqn Pout_fund=Spectrum[1]
Eqn Gain=Spectrum[1]-Pin
Eqn Pload_gain_transducer=Pout_fund-Pin
```



Task -1: Harmonic Balance

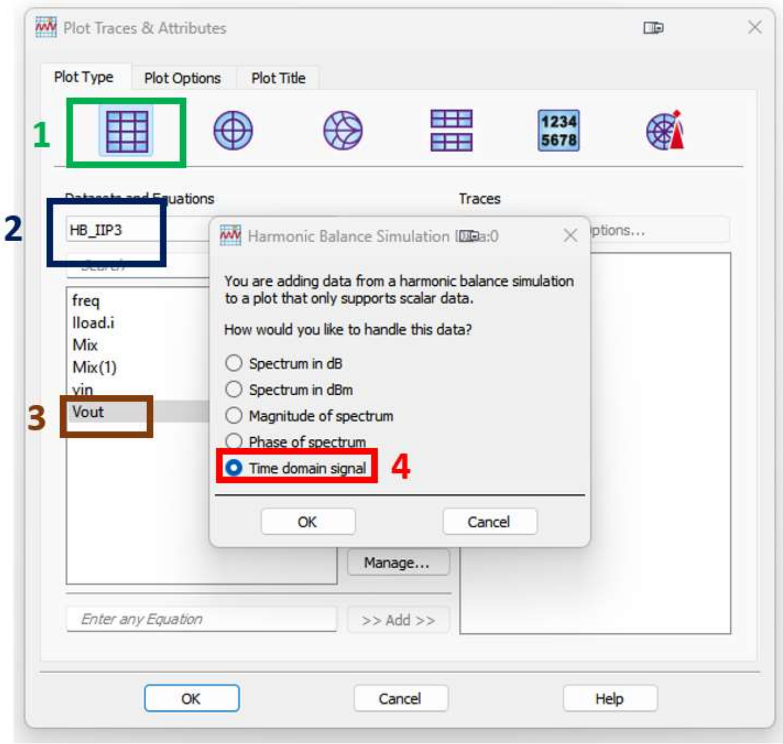
- To plot the graphs, click on the cartesian plot box and drag it to the graphing window.
- Under the datasets menu, search for equations. [1]
- From the equations plot the necessary variables as shown. [2]
- Select "**Add Vs**" to specify the X-axis you prefer [3]
- Select the dataset you want for the X-axis. [4]
- Select the Variable and plot. [5]



These are the equations that you setup in the DDS window.

Task -1: Harmonic Balance

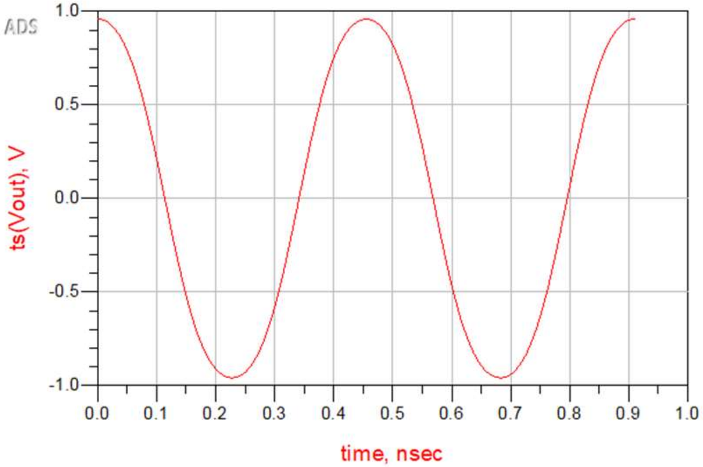
- To plot the time-domain signal in the plotting menu:
- Select the cartesian plot. [1]
- In the dataset select the name of your schematic. [2]
- Select the input and output nodes. [3]
- Select the time domain signal and plot the graph. [4]



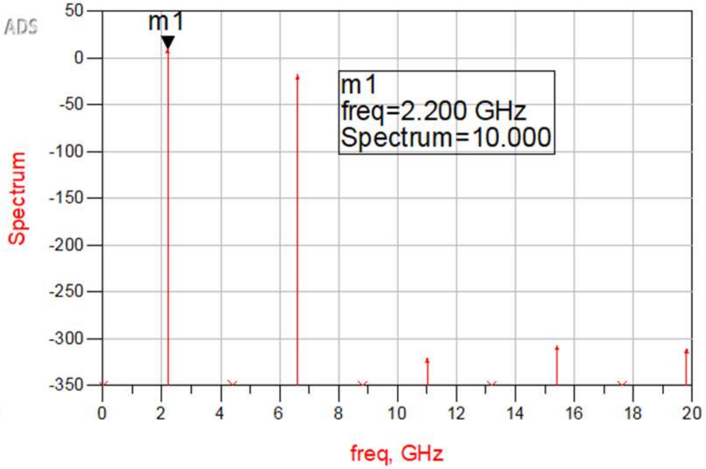
Task -1: Harmonic Balance REPORT

Plotting (Single Pin & freq)

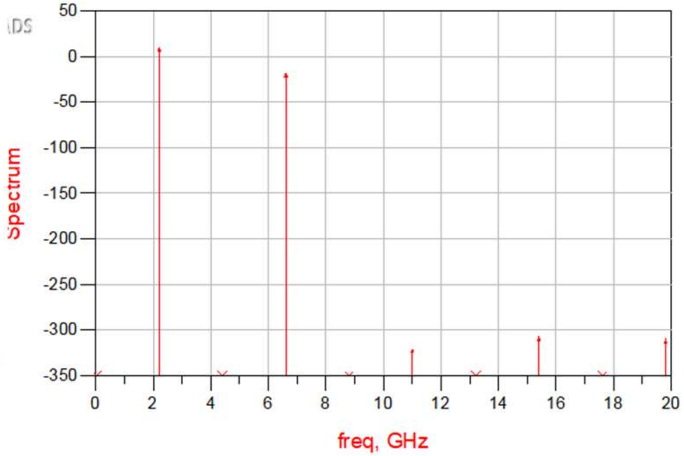
Please use this plot as reference.
Set the scales and the points of the graph ccordingly.



Vout vs. Time



Spectrum vs. Frequency

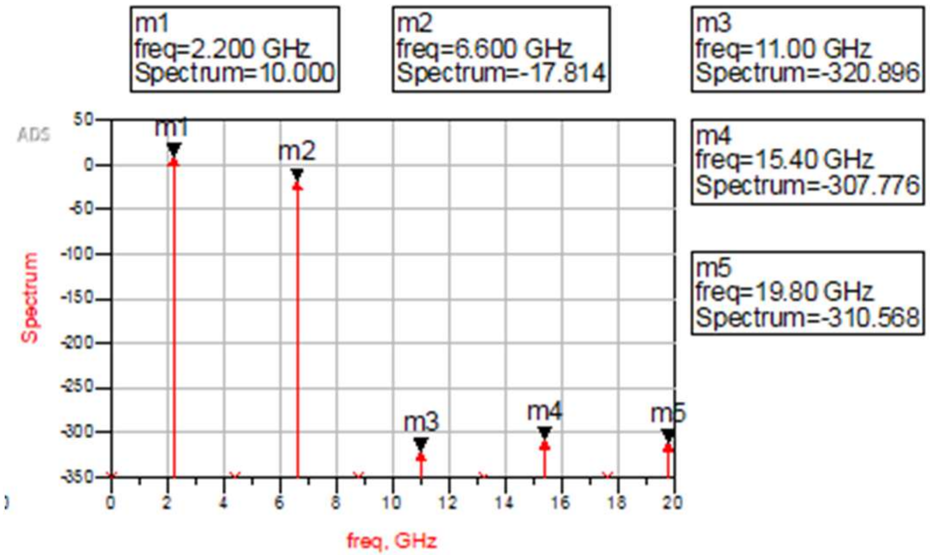


- To modify the scales, double click on the graph and go to the plot options window.
- **Disable the power sweep**
- Specify the scale according to your requirements
- Mark the P1-dB point.
- Report values.

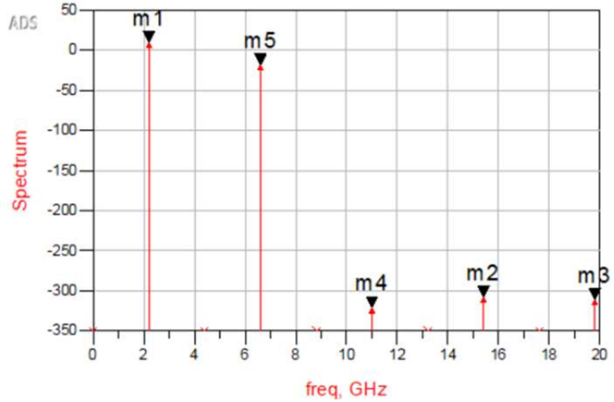
When you disable the power sweep, it will default to the Pin value entered in the schematic VAR.
RF_freq is set to 2.2 GHz in schematic, so you should see the highest power tone at 2.2GHz.

Task -1: Harmonic Balance REPORT

Plotting (Single Pin & freq)



Please use this plot as reference.
Set the scales and the points of the graph accordingly.

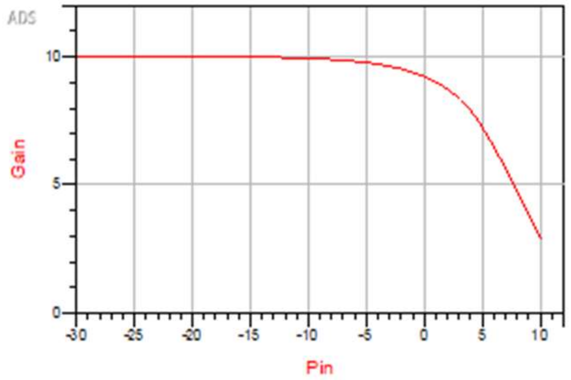


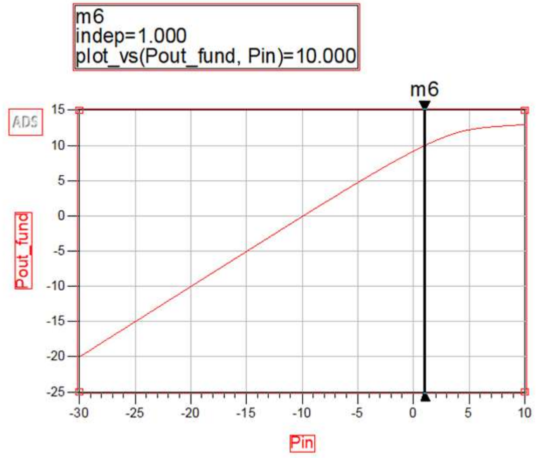
Output Spectrum	SI Unit	Value
Fundamental	dBm	10
3rd harmonic	dBm	-17.814
5th harmonic	dBm	-320.896

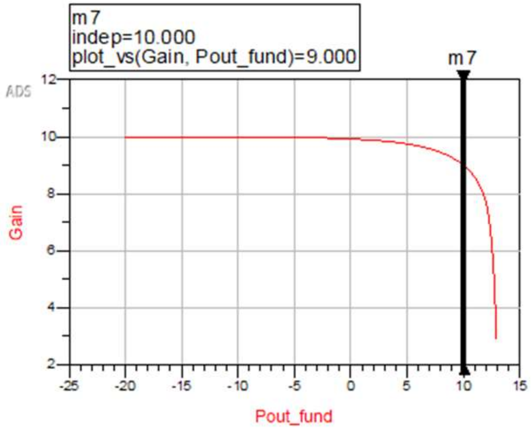
- To modify the scales, double click on the graph and go to the plot options window.
- Specify the scale according to your requirements
- Mark the harmonic components
- Report the magnitude of each component.

Task -1: Harmonic Balance REPORT

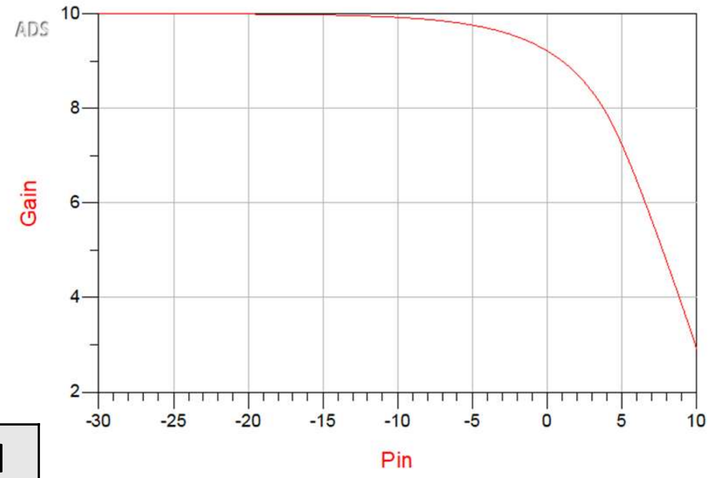
Plotting w/varying Pin







Please use this plot as reference.
Set the scales and the points of the graph accordingly.



	SI Unit	Simulated Value
Gain	dB	10
P1-dB (Input)	dBm	1
P1-dB (Output)	dBm	10

- To modify the scales, double click on the graph and go to the plot options window.
- Specify the scale according to your requirements
- **Mark the P1-dB point. Remember, this is the point when gain has dropped by 1dB from its low power (small signal) gain.**
- Report values.

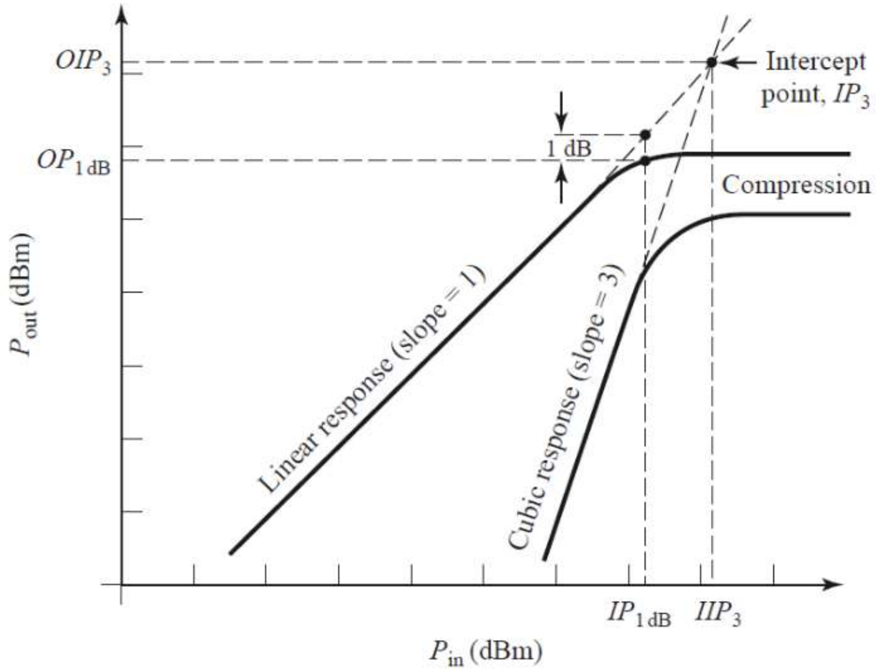
Remember to re-enable the power sweep.

Task -2: 2-tone Harmonic Balance IIP3 - Intro

Introduction:

Third order intercept point is a hypothetical point where the power of third order components will reach to the same level of fundamental component's power.

- The two curves in the figure to the left represent the growth of the first and the third harmonic components.
- The hypothetical point where the two lines intercept (Trend line of the Fundamental and 3rd harmonic) is called the third intercept point.
- The corresponding input power is called IIP3
- The corresponding output power is called OIP3



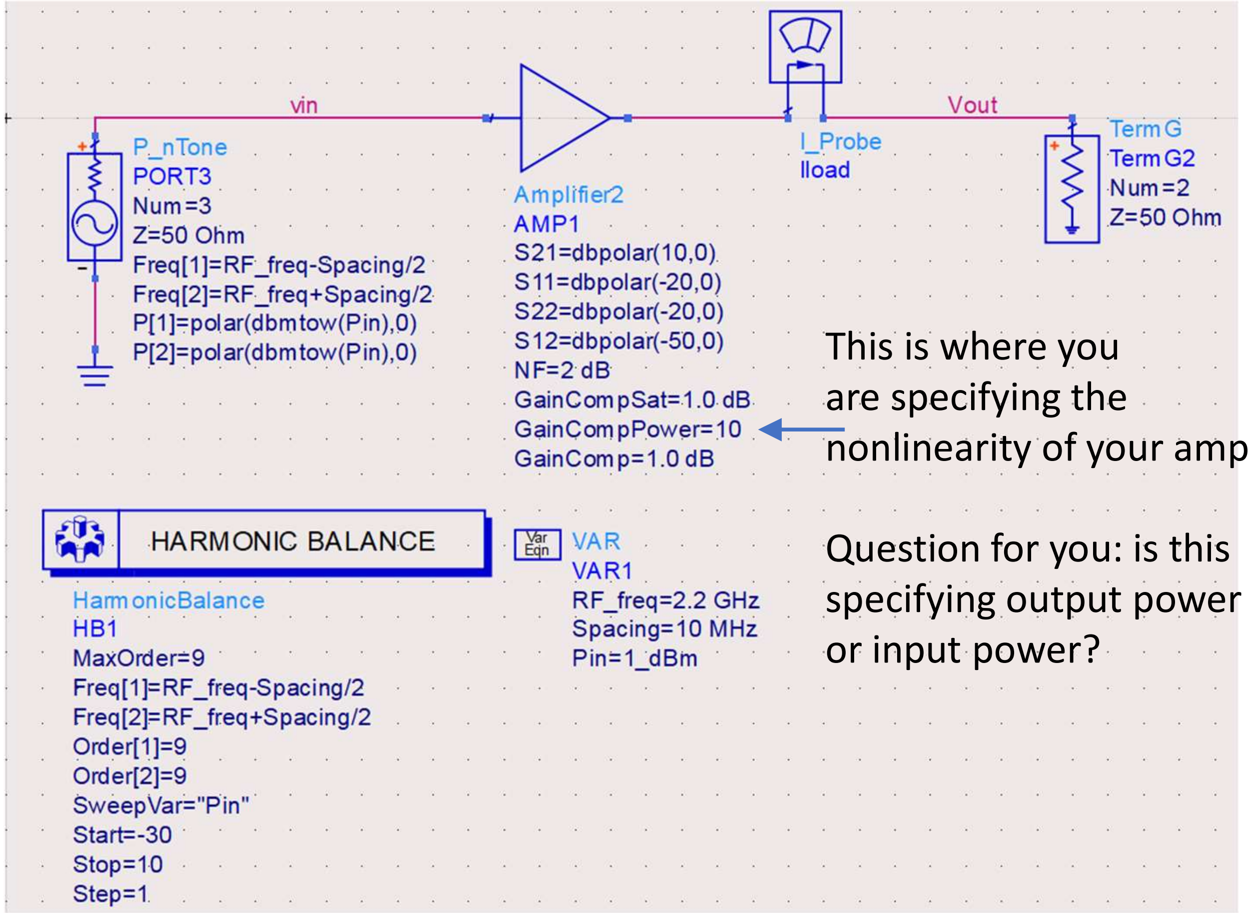
* Image courtesy Analog Devices

Task -2: 2-tone Harmonic Balance

Working with the tool:

- In the palette window, search for **"P-nTone".**
- Connect the ground terminal.
- Repeat the same steps as in task-1 and set the values in the schematic to mimic the ones in this image.

Question for you: is the "GainCompPower" specifying output power or input power?
You need to know this to make your hand calculations.



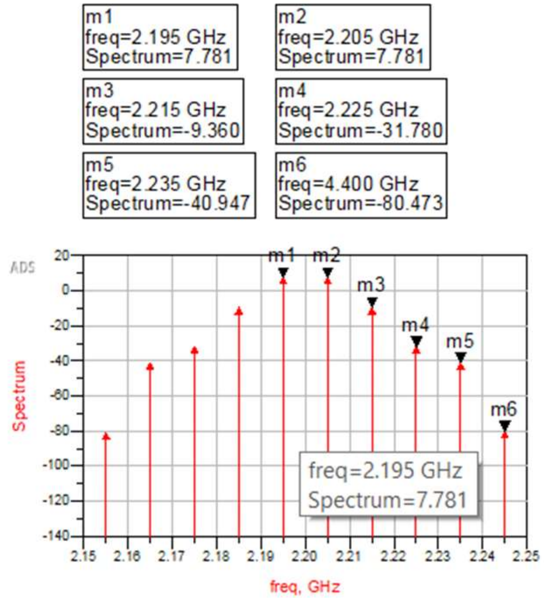
Task -2: 2-tone Harmonic Balance

- After running the simulation, in the DDS (Graph) window, please key in these equations.
- To better understand the mixing products (equations) please refer to the appendix.

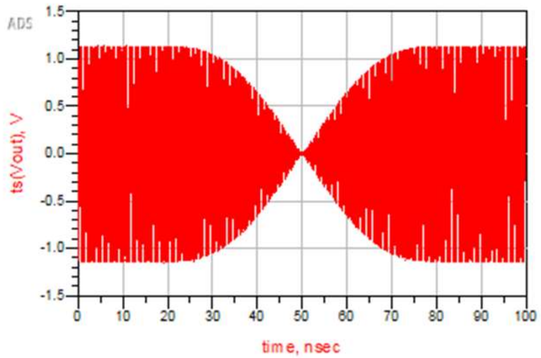
```
Eqn Spectrum_W=0.5*real(Vout*conj(Iload.i))
Eqn Spectrum=10*log(Spectrum_W)+30
Eqn Pfund_low =mix(Spectrum,{1,0},Mix)
Eqn Pfund_high=mix(Spectrum,{0,1},Mix)
Eqn P3rdOrd_low=mix(Spectrum,{2,-1},Mix)
Eqn P3rdOrd_high=mix(Spectrum,{-1,2},Mix)
Eqn Pload_dBm=10*log(Pload_W1+Pload_W2)+30
Eqn Pload_W1 = mix(Spectrum_W,{1,0},Mix)
Eqn Pload_W2=mix(Spectrum_W,{0,1},Mix)
Eqn P5thOrd_low=mix(Spectrum,{3,-2},Mix)
Eqn P5thOrd_high=mix(Spectrum,{-2,3},Mix)
Eqn Pout_fund=Spectrum[1]
Eqn Gain=Spectrum[1]-Pin
Eqn Pload_gain_transducer=Pload_dBm-Pin
```

Task -2: 2-tone Harmonic Balance **REPORT**

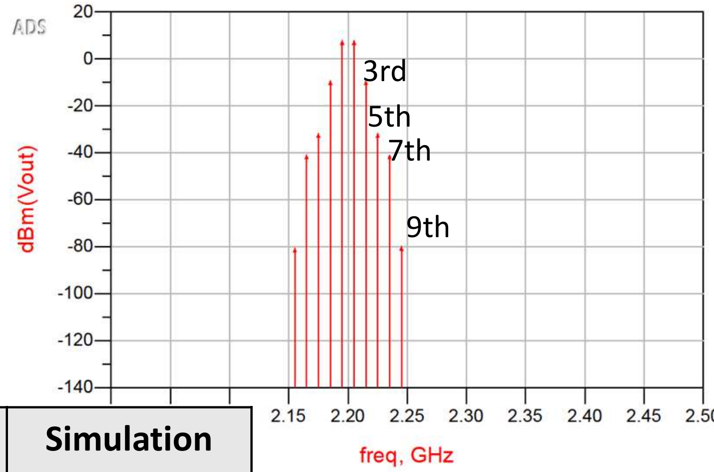
Plotting (Single Pin & freq)



Output Spectrum vs. Frequency



Vout vs. Time



	SI Unit	Calculation	Simulation
P- fundamental (output)	dBm	**7.781**	7.781
P- 2nd order Intermod Tone	dBm	**0**	-80.473
P- 3rd order Intermod Tone	dBm	-8.92	-9.360
P - 5th order Intermod	dBm	--	-31.78

You do not need to hand calculate the 5th harmonic.

We specified up to 9^{th} order distortion in our setup. So, we expect up to 9^{th} order intermod tones.

You can get plot like above if you zoom-in frequency. Make note of the x axis.

Task -2: 2-tone Harmonic Balance REPORT

P_{fund}

$$V_{out\,fund} = K_1 A + \frac{9 K_3 A^3}{4} = 3.162\,(0.354) + \frac{9}{4}(-3.404) \times (0.354)^3$$

$$\Rightarrow 1.1193 + (-0.3397) \Rightarrow 0.7795$$

$$V_{out\,rms} = 0.7795/\sqrt{2} = 0.551\,V$$

$$P_{out\,fund} = V_{rms}^2 / R = 6\,mW \Rightarrow 7.781\,dBm$$

P_{IM3}.

$$P_{IM2} = P_{O2} = K_2 A^2 = 0$$

$$K_3 = -3.404$$

$$A_{IM3} \Rightarrow \frac{3 K_3 A^3}{4} = \frac{-3 \times 3.404 \times (0.354)^3}{4}$$

$$\Rightarrow A_{IM3} = 0.1132\,V$$

$$V_{IM3} = 0.1132/\sqrt{2} = 0.08\,V.$$

$$P = V^2/R = (0.08)^2/50 = 0.128\,mW$$

$$P_{IM3} = 10\log(0.128) = -8.92\,dBm$$

$$P_{IM3} = -8.92\,dBm$$

Task -2: 2-tone Harmonic Balance _ HINTS

Hints for Hand Calculations of 2^{nd} and 3^{rd} order intermodulation tone power:

In order to find the power of the tones, you can model the nonlinearity of the amplifier with a Taylor series expansion (slides 3-8 of L10).

The second and third order tones are dependent on amplitude of the fundamental signal (A_1, A_2), as well as the constants (k_1, k_2, etc). Previous slide gives you the constants.

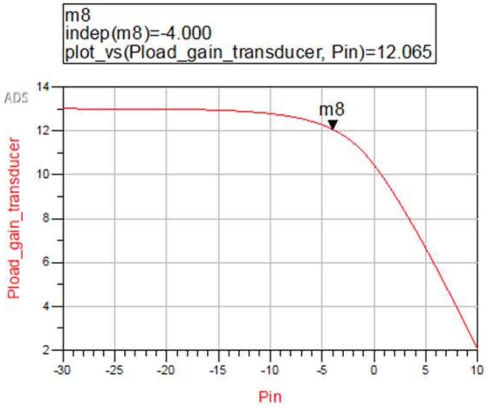
Find the amplitudes of the signals existing from the third order distortion (at 2f2-f1 and 2f1-f2) and the second order distortion. See L10. Slides 3, 4, 6 for part of this derivation.

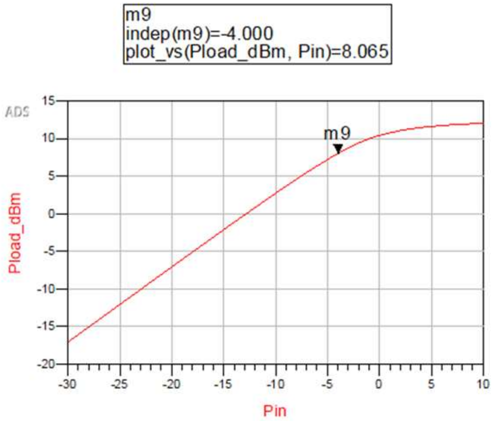
Then convert the amplitudes that you calculate into power in dBm and enter them in the table on slide 19. Check out example in L10 slides 15-16 (same slides in L11). Your load is 50 ohms.

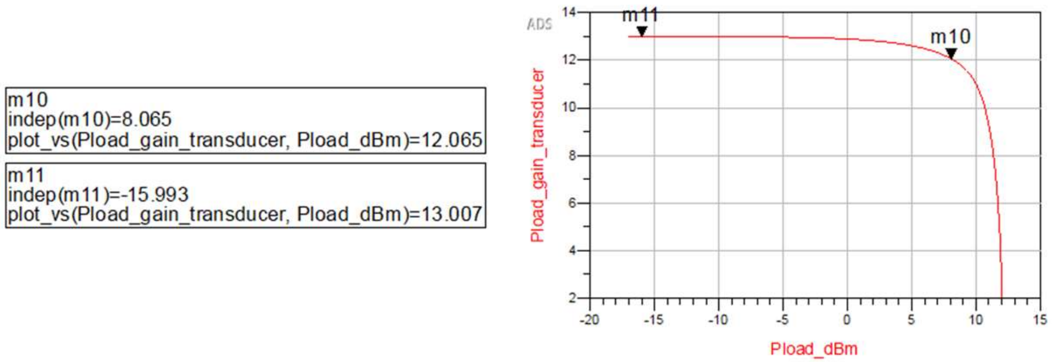
NOTE: you can also calculate P_fundamental at the output using the Taylor series expansion and this will include the gain compression caused by k_3.

Task -2: 2-tone Harmonic Balance REPORT

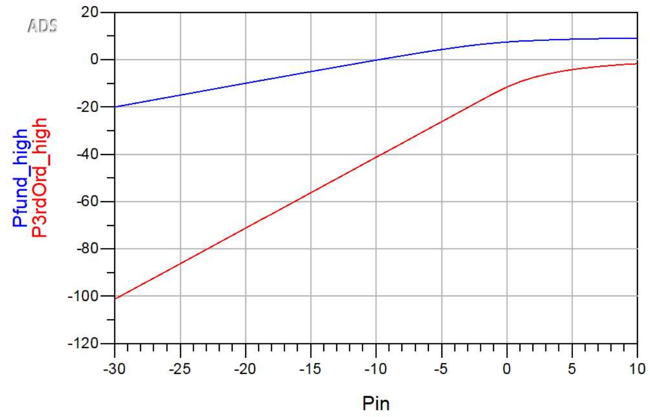
Plotting w/varying Pin







Please use this plot as reference.
Set the scales and the points of the graph accordingly.

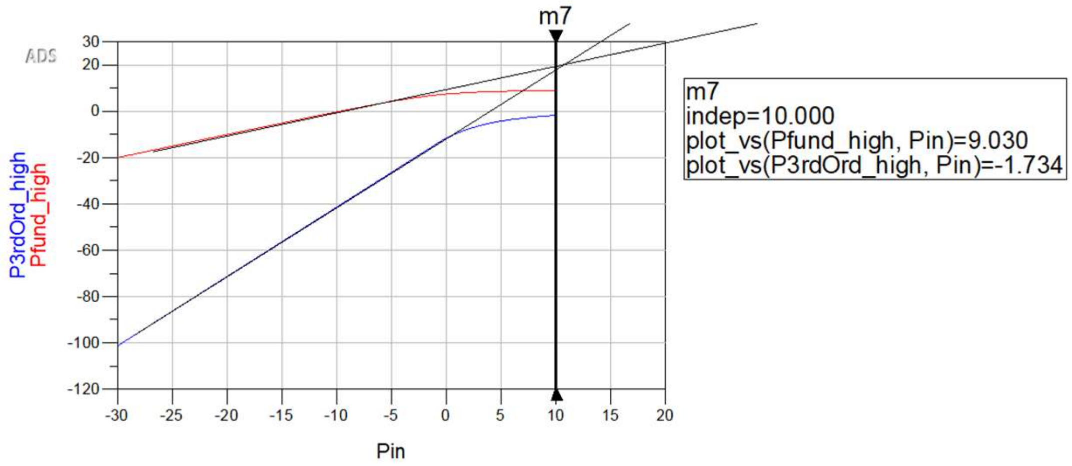


- To modify the scales, double click on the graph and go to the plot options window.
- Specify the scale according to your requirements
- **Mark the IIP3 point, through extrapolating the lines to the point when they meet.**
- Report the values.

Remember to re-enable the power sweep.

Task -2: 2-tone Harmonic Balance REPORT

Plotting w/ varying Pin



	SI Unit	Calculation	Simulation
Gain (for small signals)	dB	**10 dB**	13
P1-dB	dBm	**IP=1** **OP=10**	IP=3.8 OP=8.065
IIP3	dBm	10.6	10 approx
OIP3	dBm	20.6	20

Task -2: 2-tone Harmonic Balance - REPORT

Method 1

$IIP_3 = IP_{1dB} + 9.6dB$

$= 1\ dBm + 9.6dB$

$IIP_3 = 10.6dBm$

$OIP_3 = IIP_3 + Gain \Rightarrow 10.6dBm + 10dB$

$OIP_3 = 20.6dBm$

Method2

$V = \sqrt{PR}$ $\quad R = 50\Omega,\ P = 1dBm = 1.258mW$

$V = \sqrt{1.258\times10^{-3}\times 50}$

$V_{rms} = 0.2507V$

$A_{IP_3} = \sqrt{\frac{4}{3}\frac{k_1}{k_3}} \Rightarrow \sqrt{\frac{4}{3}\times\frac{3.162}{-3.404}} = 1.1134$

$V_{peak} = A = V_{rms}\sqrt{2} = 0.2507\times\sqrt{2} = 0.354V$

$A\,dB = -9dB$

$A_{IP_3} = 1.113$ in dB $\Rightarrow 0.929dB$

$IM_3 = 2(A - A_{IP_3})dB = 2(-9 - 0.929)$

$= -19.85\,dB$

$IM_3 = 2(P_{in} - IIP_3)$

$\Rightarrow IIP_3 = P_{in} - IM_3/2 = 1dBm - (-19.85/2)$

$IIP_3 = 10.925dBm$

$IM_3\,dB = 2(P_{out} - OIP_3) \Rightarrow OIP_3 = P_{out} - IM_3/2$

$= 7.781dBm - (-9.925)dB$

$OIP_3 = 17.706\,dBm$

$OIP_3 = IIP_3 + Gain$

$OIP_3 = 10.925dBm + 10dB$

$OIP_3 = 20.925dBm$

Task -2: 2-tone Harmonic Balance _ HINTS

Hints for Hand Calculations of IIP3/OIP3 METHOD 1:

P1dB is given to you in the schematic (you specified this in the amplifier). You also simulated this in Task 1. You can pick to use the one from schematic or the simulated one from Task 1.
Gain is calculated in your Equations in the .dds window, if you use simulated one.
Your amplifier parameters also have these values defined. You will need these values.

There is a theoretical relationship between P1dB and IIP3 in your lecture slides, L10 slide 14

If you know input P1dB, you can find IIP3. From IIP3 and Gain, you can find OIP3.

If you know output P1dB, you can find OIP3. From OIP3 and Gain, you can find IIP3.

Enter values into table on slide 23.

Task -2: 2-tone Harmonic Balance _ HINTS

Hints for Hand Calculations of IIP3/OIP3 METHOD 2:

You have already hand calculated the fundamental and intermodulation tones in slide 19. From this, you may find IM3 and then solve for OIP3. Use your equation derived in HW2 problem 4a.

P_o is fundamental power. P_{o3} is third order power.

Use the theoretical relationship between IIP3 and OIP3 to find IIP3 from OIP3.

Enter values into table on slide 23.

Task -2: 2-tone Harmonic Balance OPTIONAL

Extra Credit of 6 points (out of 60) if you complete the following:

- Calculate the OIP3/IIP3 using each of the methods, Method 1 and Method 2, and include both hand analyses in this report.
- Compare the results between methods in a paragraph. Are these different results? Why?

The result for method 2 is better than method 1 as the values are closer to simulations

- If results are different, which method is closer to the simulated values?

NOTE: I will let your grade go above 60/60 on this assignment if you are over 60 points.

Summarize Your Learnings – REPORT

Fill in on this slide:

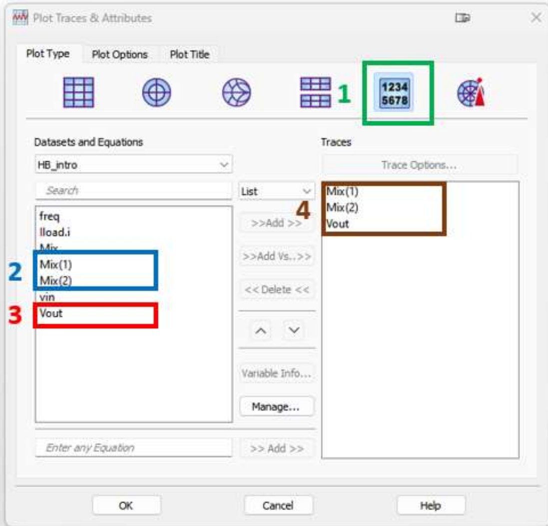
Compare your IIP3/OIP3 hand calcs to simulations. Are they very different? If so, what do you believe causes the difference?
***Both the simulations and hand calculations were almost same**
Do you have any key takeaways that you have learned from this project?
Learned the working of harmonic balance and linearity metrics

Appendix

- Lang, Hans-Dieter and Xingqi Zhang. “The Harmonic Balance Method.” (2013).

Mixing component indices:

- Fundamental is represented by {0,1} or {1,0}.
- Third order component is {2,-1} or {-1,2}.
- Fifth order component is {3,-2} or {-2,3}.
- To view the combinations of the mixing indices and identify the frequency components, one can follow the steps mentioned in the figure.



freq	Vout	Mix(1)	Mix(2)
0.0000 Hz	2.231E-5 / 0.0...	0	0
10.00 MHz	2.683E-5 / -2....	-1	1
20.00 MHz	1.205E-5 / 18...	-2	2
30.00 MHz	4.246E-5 / 18...	-3	3
40.00 MHz	4.606E-5 / 18...	-4	4
2.155 GHz	2.911E-5 / -7....	5	-4
2.165 GHz	0.003 / -2.738...	4	-3
2.175 GHz	0.008 / -4.995...	3	-2
2.185 GHz	0.108 / 180.000	2	-1
2.195 GHz	0.775 / 1.960...	1	0
2.205 GHz	0.775 / -8.669...	0	1
2.215 GHz	0.108 / -180.0...	-1	2
2.225 GHz	0.008 / 7.553...	-2	3
2.235 GHz	0.003 / -1.099...	-3	4
2.245 GHz	3.179E-5 / 1.2...	-4	5
4.360 GHz	1.712E-5 / -1...	5	-3
4.370 GHz	7.182E-6 / 18...	4	-2
4.380 GHz	1.389E-5 / 1.4...	3	-1
4.390 GHz	3.440E-5 / 2.3...	2	0
4.400 GHz	2.995E-5 / -6....	1	1
4.410 GHz	5.322E-6 / 18...	0	2
4.420 GHz	4.496E-5 / -1...	-1	3
4.430 GHz	5.238E-5 / 18...	-2	4
4.440 GHz	1.448E-5 / -1...	-3	5
6.555 GHz	1.914E-4 / -1...	6	-3
6.565 GHz	0.002 / -3.068...	5	-2
6.575 GHz	0.006 / -1.149...	4	-1
6.585 GHz	0.030 / 180.000	3	0
6.595 GHz	0.108 / 180.000	2	1
6.605 GHz	0.108 / 180.000	1	2
6.615 GHz	0.030 / -180.0...	0	3
6.625 GHz	0.006 / -1.681...	-1	4
6.635 GHz	0.002 / -3.595...	-2	5
6.645 GHz	1.873E-4 / -1...	-3	6
8.760 GHz	1.574E-5 / 4.9...	6	-2
8.770 GHz	1.108E-5 / -2....	5	-1
8.780 GHz	1.604E-5 / 2.6...	4	0
8.790 GHz	1.876E-5 / -1....	3	1
8.800 GHz	2.733E-6 / -1...	2	2
8.810 GHz	3.995E-5 / -1...	1	3
8.820 GHz	5.094E-5 / -1...	0	4
8.830 GHz	6.636E-6 / -1...	-1	5
8.840 GHz	6.954E-5 / 1.4...	-2	6
10.96 GHz	4.060E-4 / 18...	7	-2
10.96 GHz	5.766E-4 / 3.8...	6	-1
10.97 GHz	0.003 / 9.980...	5	0
10.98 GHz	0.006 / -5.859...	4	1
10.99 GHz	0.008 / -5.245...	3	2

Appendix

- Lang, Hans-Dieter and Xingqi Zhang. “The Harmonic Balance Method.” (2013).

Eqn Spectrum_W=0.5*real(Vout*conj(Iload.i))	Spectrum identified as a function of complex current and voltage **P = V*I/2**
Eqn Spectrum=10*log(Spectrum_W)+30	Spectrum in watts is converted to dBm
Eqn Pout_fund=Spectrum[1]	Output fundamental tone is separated with the mixing factor -1
Eqn Gain=Spectrum[1]-Pin	Gain = (Output power in dBm) – (Input Power in dBm)
Eqn Pload_gain_transducer=Pout_fund-Pin	