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Nonlinear Simulation of RF IC Amplifiers in Keysight Genesys and SystemVue

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Introduction

Linear and nonlinear RF circuit simulation have traditionally occupied different domains. To simulate cascaded small signal gain and loss, RF equipment designers have traditionally turned to S-parameter device models, which are widely available. Nonlinear simulation has traditionally been more challenging due to the lack of availability of data in digital form (for example, IP3, P1dB, and noise), along with a historical absence of frequency-variant model structures in popular RF simulators. RF circuit designers have typically resorted to using homemade spreadsheets that calculate cascaded noise and distortion. These spreadsheets, however, struggle to simulate system-level characteristics, such as error vector magnitude (EVM) and adjacent channel leakage ratio (ACLR), which become relevant when the signal chain is driven by modulated signals.

This article will explore some RF amplifier model structures that combine linear S-parameter data with nonlinear data such as noise figure, IP3, P1dB, and P_{SAT}. We will also show the results of system-level simulations to assess how accurately real-world behavior is modeled.

S-Parameters

S-parameter datasets are by far the most widely used RF simulation model. These are standardized tabular datasets consisting of input return loss, gain, reverse isolation, and output return loss vs. frequency, all in vector format. The data is generally collected under small signal conditions with drive signals well backed off from signal compression points. S-parameters are typically used to simulate cascaded gain, to design input and output matching networks, and to assess stability. However, they contain no information about a device's noise, compression, or distortion characteristics.

Table 1. A Typical Sys-Parameter Dataset

ADPA7002AEHZ									
Test Conditions: V_D = 5 V; I_D = 600 mA; Temperature = 25°C									
Freq (MHz)	Gain (dB)	Noise Figure (dB)	OP1dB (dBm)	RISO (dB)	OIP3 (dBm)	S11m (dB20)	S11a (°)	S22m (dB20)	S22a (°)
20,000	16.95	8.74	26.56	–67.721	36.44	–7.75	173.729	–11.557	147.426
21,000	17.68	8.24	26.91	–73.233	36.76	–8.517	80.526	–11.122	62.568
21,500	17.93	7.9	27.03	–68.951	36.88	–9.589	34.318	–11.311	22.785
22,000	17.93	7.36	27.17	–61.943	37.15	–10.697	–10.322	–11.509	–19.276
23,000	17.65	6.99	27.52	–59.98	37.96	–12.651	–103.636	–11.98	–97.33
23,500	17.56	6.81	27.74	–61.879	38.41	–14.063	–151.565	–12.827	–134.022
24,000	17.47	6.63	27.96	–80.139	38.73	–15.938	165.692	–12.945	–168.222
24,500	17.37	6.43	28.34	–58.564	38.86	–16.997	121.508	–13.498	148.481
25,000	17.29	6.21	28.76	–61.205	38.91	–17.923	62.549	–15.611	113.253
25,500	17.21	6.09	29.13	–78.557	38.99	–19.426	–7.015	–17.18	69.575
26,000	17.24	5.9	29.43	–57.547	39.12	–18.303	–66.409	–17.852	6.777
26,500	17.15	5.83	29.58	–52.009	39.13	–15.27	–111.709	–17.11	–77.28
27,000	17.18	5.77	29.67	–46.65	39.19	–12.005	–156.238	–14.802	–149.404
27,500	17.11	5.79	29.75	–46.267	39.31	–10.127	156.189	–13.119	156.549
28,000	17.06	5.68	29.81	–47.084	39.38	–9.77	110.867	–11.898	106.852
29,000	17.15	5.49	30.03	–44.2	39.84	–14.726	26.262	–12.296	20.551
30,000	17.09	5.53	30.07	–49.031	40.1	–19.255	–50.641	–10.565	–71.449

Keysight Sys-Parameters

Table 1 shows a portion of the sys-parameter dataset for ADPA7002, an 18 GHz to 44 GHz, 0.5 W power amplifier. The sys-parameter device model structure has been defined by Keysight for use in its PathWave RF Synthesis (Genesys) and PathWave System Design (SystemVue) RF circuit and system simulators. The tabular structure of the dataset consists of S-parameter data combined with noise, third-order intermodulation, and 1 dB compression data indexed vs. frequency. These datasets provide enough information to enable simulation of the RF signal level, cascaded gain, and reverse isolation. However, the inclusion of IP3, P1dB, and noise figure data opens up the possibility to simulate RF power sweeps and signal-to-noise ratio. Higher order signal characteristics such as ACLR and EVM can also be simulated over the operating frequency range of the device.

Analog Devices maintains an extensive RF amplifier and mixer sys-parameter library, which is available for download and also included with Keysight Genesys and SystemVue installations. Figure 1 shows a screenshot from Keysight Genesys. The Analog Devices sys-parameter library is readily accessible via the **Part Selector**. The sys-parameter device model for each device consists of the data shown in Table 1, along with additional information contained in the model's **Properties** window. This additional data consists of power supply information along with default offsets for P_{SAT} and OIP2, relative to OP1dB.

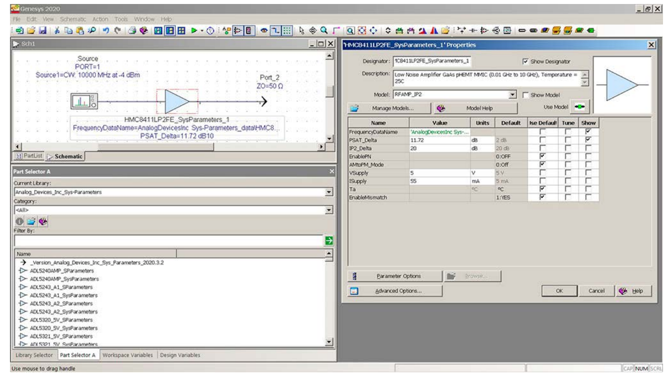

Figure 1. Screenshot from Keysight Genesys showing a typical sys-parameter model.

Assessing the Accuracy of Sys-Parameter Models

To assess the accuracy of sys-parameter models, we will now perform a series of comparisons between measured results and simulations. Figure 2 shows measured and simulated results for a power sweep at 10 GHz of HMC788A, a 10 MHz to 10 GHz RF gain block. We can see that the simulated power sweep matches measured data quite closely. The simulator is using the device's gain and OP1dB data along with a P_{SAT}–Delta to generate the plot shown. In this case the P_{SAT}–Delta is 2 dB. This results in a P_{SAT} value that is 2 dB above the OP1dB level, which is a typical default for GaAs RF amplifiers.

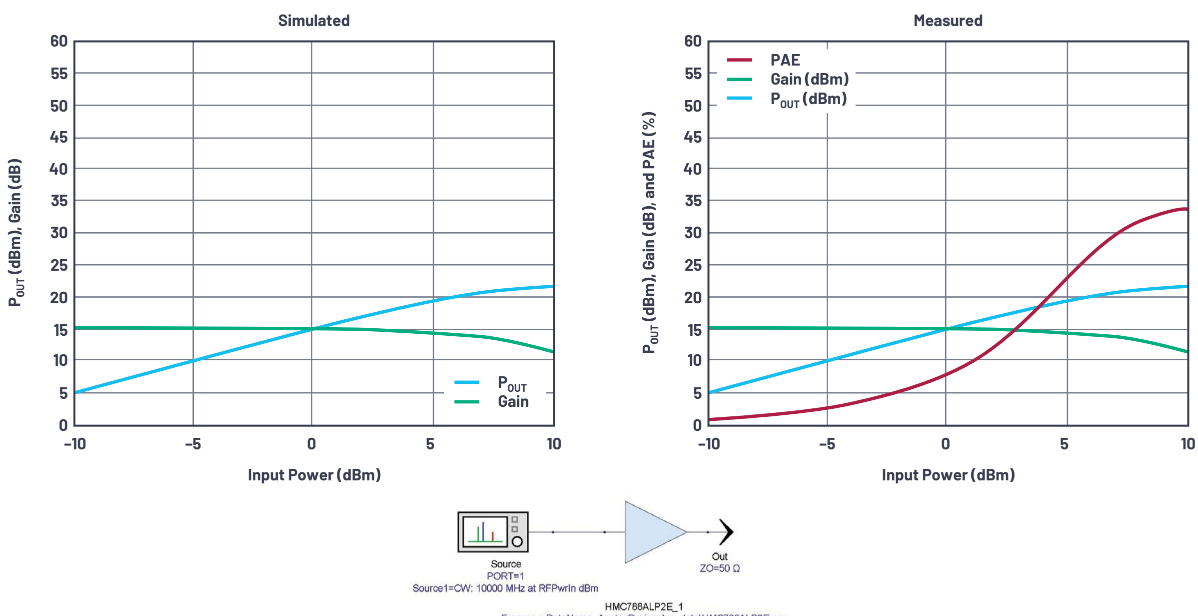

Figure 2. Measured and simulated power sweep of a gallium arsenide (GaAs) RF amplifier.

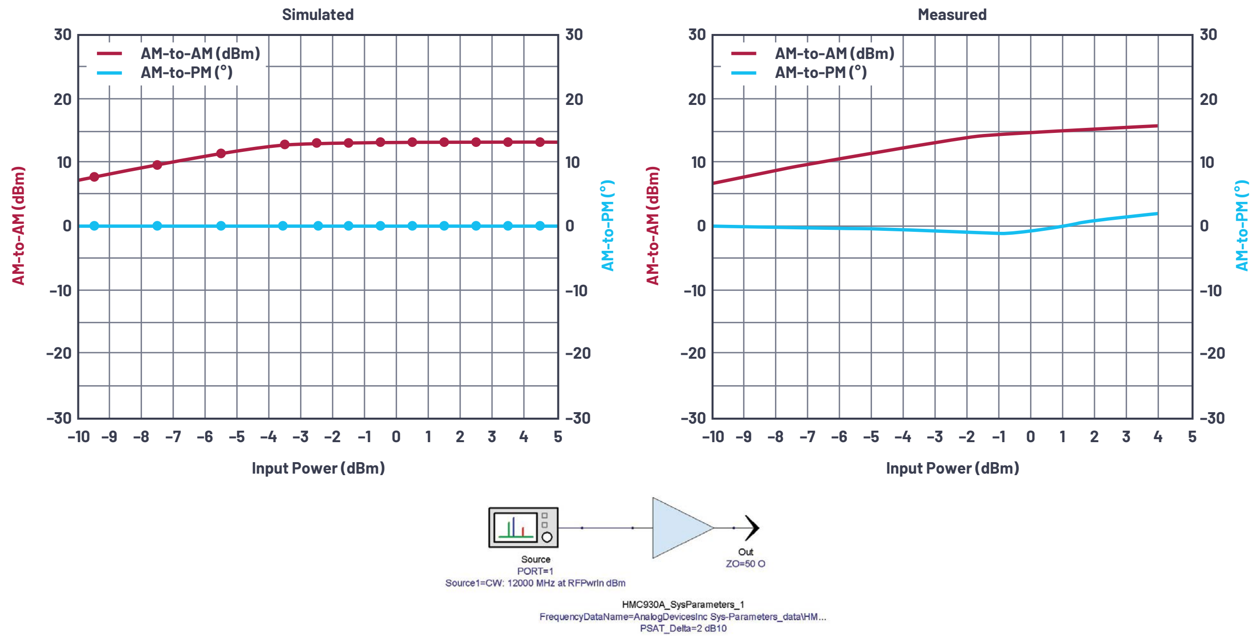

Figure 3. Simulation and measurement of AM-to-AM and AM-to-PM distortion.

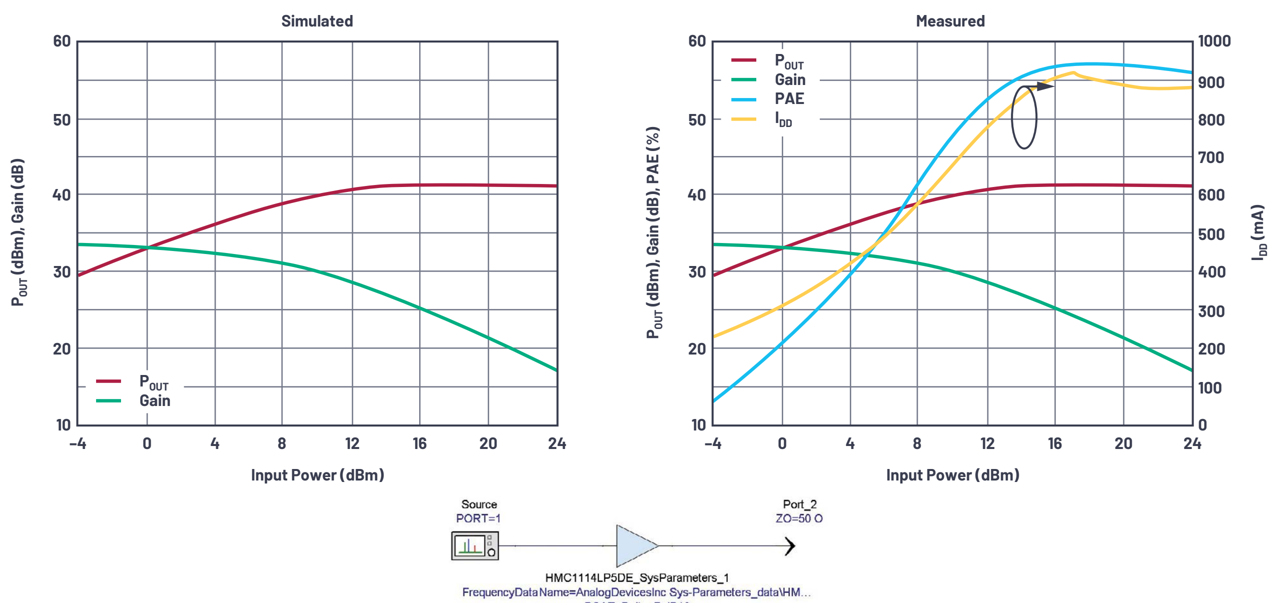

Figure 4. Simulated and measured power sweep of HMC1114, a 10 W GaN amplifier at 3.2 GHz.

AM-to-AM and AM-to-PM Distortion

To take a closer look at simulated compression characteristics, we can look at AM-to-AM and AM-to-PM distortion. Measured and simulated results are shown in Figure 3 for HMC930A. Measured AM-to-AM distortion matches quite closely with simulation. However, the simulation indicates that there is no AM-to-PM distortion, which is not correct. This is because the device model and dataset only contain small signal phase information (that is, S21). While the simulator can use OP1dB and P_{SAT}_Delta data from the device model to estimate AM-to-AM distortion, it does not have any large signal S-parameter data to work with. This is an instance where the use of a more elaborate model such as the X-parameter format—X-parameter models have built-in level-dependent S-parameters—would be appropriate.

Simulating a Power Sweep for a Gallium Nitride Amplifier

Figure 4 shows a power sweep at 3.2 GHz for HMC1114LP5DE, a 10 W gallium nitride (GaN) RF amplifier. GaN RF amplifiers tend to have a much softer compression characteristic than GaAs devices. This necessitates an adjustment of the P_{SAT}_Delta—that is, the difference between the 1 dB compression point and the saturation point. In this case, that delta has been set to 7 dB based on observed measurements. While the simulator will in some cases generate a warning because of the large delta, it will still simulate correctly and produce a result that closely matches measured performance.

ACLR Simulation

As we move away from CW measurements and simulations toward modulated signal behavior, the value of a sys-parameter dataset increases. While information on device gain, compression, IP3, and noise figure are readily available in device data sheets, plots showing performance with modulated signals are unlikely to be found in the data sheets of devices designed for general-purpose use. In addition, metrics such as ACLR and EVM are not easily predicted without simulation or measurement.

Figure 5 shows simulated results for a 2140 MHz power sweep of ADL5320, a 0.25 W driver amplifier, when driven by a 5 MHz wide carrier. The simulated carrier consists of 11 evenly spaced subcarriers, and ACLR is measured at a 5 MHz carrier offset.

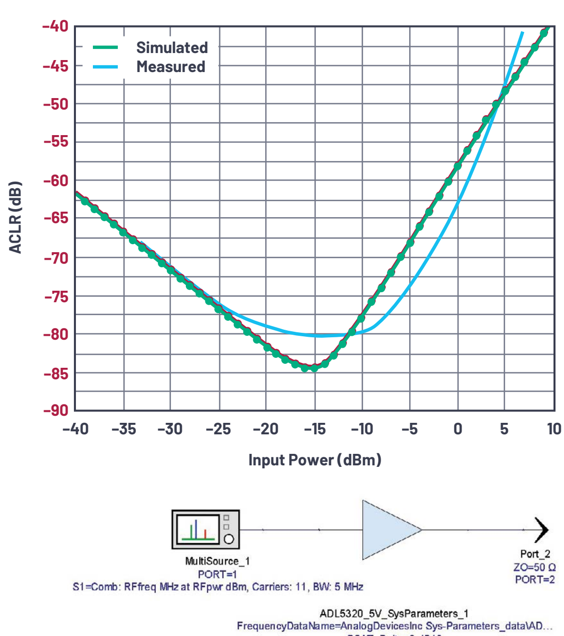

Figure 5. ACLR simulation.

Simulation suggests that the ACLR reaches its optimum value at an input power of –15 dBm. Below this input power, ACLR degrades dB-for-dB with input level. This region of the plot is being dominated by the noise figure data in the dataset. As the input power increases above –15 dBm, the ACLR degrades at a rate that closely correlates with the device's IP3. It's significant to note that the results of this simulation rely on both noise figure data (at low power) and IP3 data (at high power) to produce an ACLR sweep that is accurate over a wide power range.

The plot also includes measured data (in blue). It does not reach the same optimum level for an input power level of –15 dBm; this is due to the limitations of the measurement setup. It is noticeable that as the input power level increases, the measured ACLR degrades faster. This is because the device's OIP3 degrades slightly with input/output power level (ideally it should not change). The IP3 in the device model's dataset is a single dataset and does not change with power level; it can be thought of as the device's small signal IP3. This is again an instance where an X-parameter model, with its more elaborate level-dependency modeling, might produce a more accurate simulation.

EVM Simulation

Sys-parameter models can also be used to reliably simulate EVM. Figure 6 shows the results of a measured and simulated sweep of EVM vs. RF power level where the input signal is a 1 MSPS, 16 QAM carrier driving ADL5602, a 50 MHz to 4 GHz gain block. This shows excellent correlation between measurement and simulation at both low and high power levels.

Temperature Simulation

The default sys-parameter dataset in the ADI library contains only ambient temperature data. However, the model can be expanded by adding additional tabs to the dataset that contains temperature data. Figure 7 shows the dataset for ADPA7007, an 18 GHz to 44 GHz, 1 W power amplifier. This dataset has individual tabs containing the same gain, noise, and distortion data but at –55°C, +25°C, and +85°C. The Genesys and SystemVue simulators use these three datapoints to generate interpolated data at other temperatures, also shown in Figure 7.

Simulation in ADS

Sys-parameter datasets are native to Keysight Genesys and SystemVue but do not work in Keysight ADS. There is a workaround for importing a sys-parameter dataset into ADS that allows noise, distortion, and compression simulations to be performed. This involves using the Amplifier2 model. The Amplifier2 model is native to Keysight ADS and provides similar functionality to sys-parameter models. Figure 8 shows an ADS schematic that includes an Amplifier2 model. The schematic also contains two data access components, DAC1 and DAC2. These DACs are used to associate the sys-parameter data with the Amplifier2 model. The noise figure, OIP3, and OP1dB data is formatted into a text file and is associated with the Amplifier2 model using the DAC1 component. The DAC2 component is used to associate the S-parameter data with the Amplifier2 model. This results in an Amplifier2 model in ADS that can be used to perform all of the same simulations that have been discussed already, but in Keysight ADS.

Care must be taken with this method. When performing RF power sweeps where the Amplifier2 model is being driven heavily into compression, the simulated performance tends to deviate significantly from observed measured performance. Also, creating an Amplifier2 model that uses S-parameter data along with noise, distortion, and compression data is best suited to devices that have good baseline input and output return loss (S11 and S22); this is the case for most of Analog Devices' RF amplifiers that do not require external RF matching components. A simpler Amplifier2 model can be created by adding scalar gain to the DAC1 component and omitting the S-parameter data (that is, omit DAC2).

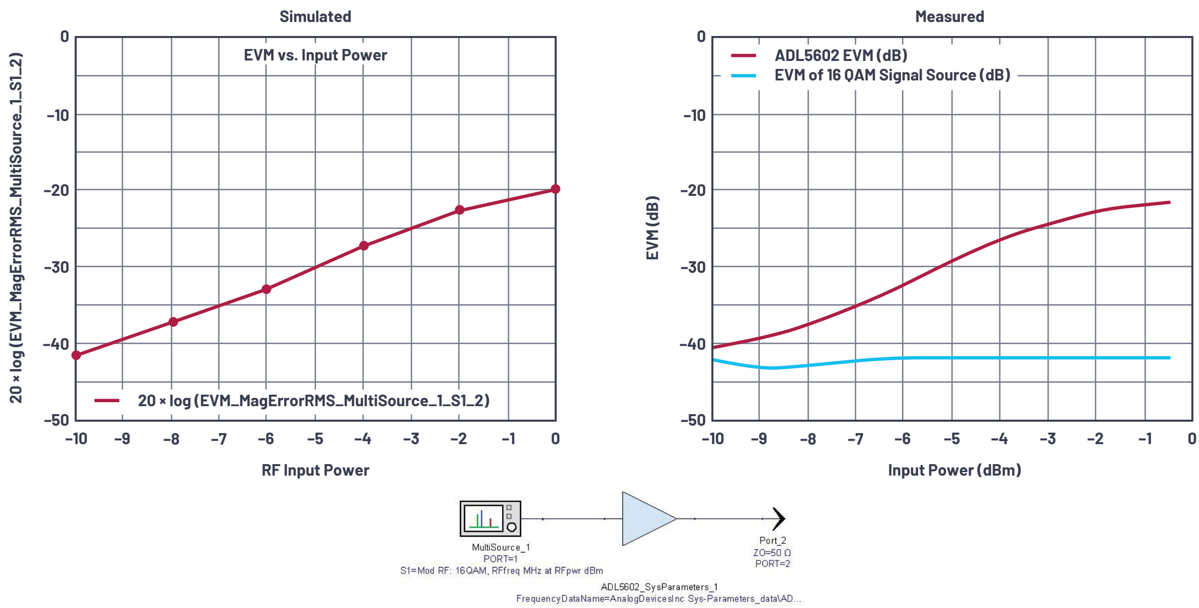

Figure 6. Simulated and measured EVM power sweep of a wideband gain block.

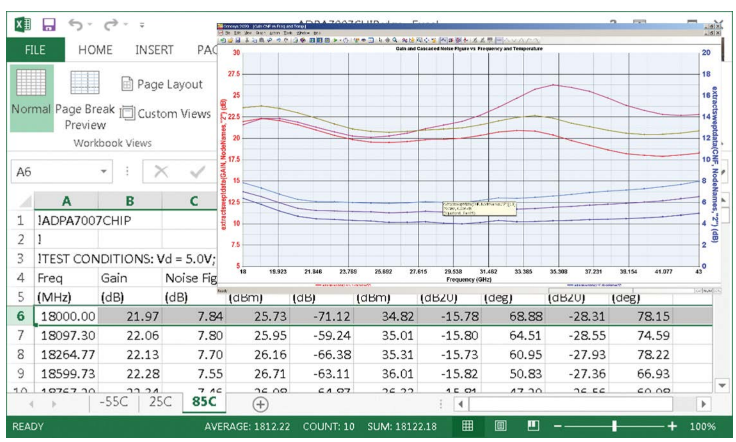

Figure 7. Simulated gain and noise figure vs. temperature for ADPA7007, an 18 GHz to 44 GHz, 1 W power amplifier.

Conclusion

Sys-parameter datasets represent a new and useful RF amplifier simulation tool. They are more powerful than S-parameters, which do not model noise, distortion, and compression. They are not as elaborate as X-parameter models, which can improve model level-dependent behavior such as AM-to-PM distortion and ACLR. However, sys-parameter models have a simple tabular structure and can be easily created by combining S-parameter data with noise figure, OIP3, and OP1dB data. Comparisons of simulated and measured data show excellent conformance. While sys-parameter models cannot be used in ADS, a relatively easy process can be followed to migrate the datasets using the Amplifier2 model structure, which is native to ADS.

Analog Devices is committed to maintaining and expanding its library of sys-parameter models. As new models are added to the library, support for temperature simulation will be added. The most up-to-date libraries for Keysight Genesys and SystemVue can be downloaded at analog.com/sys-parameters.

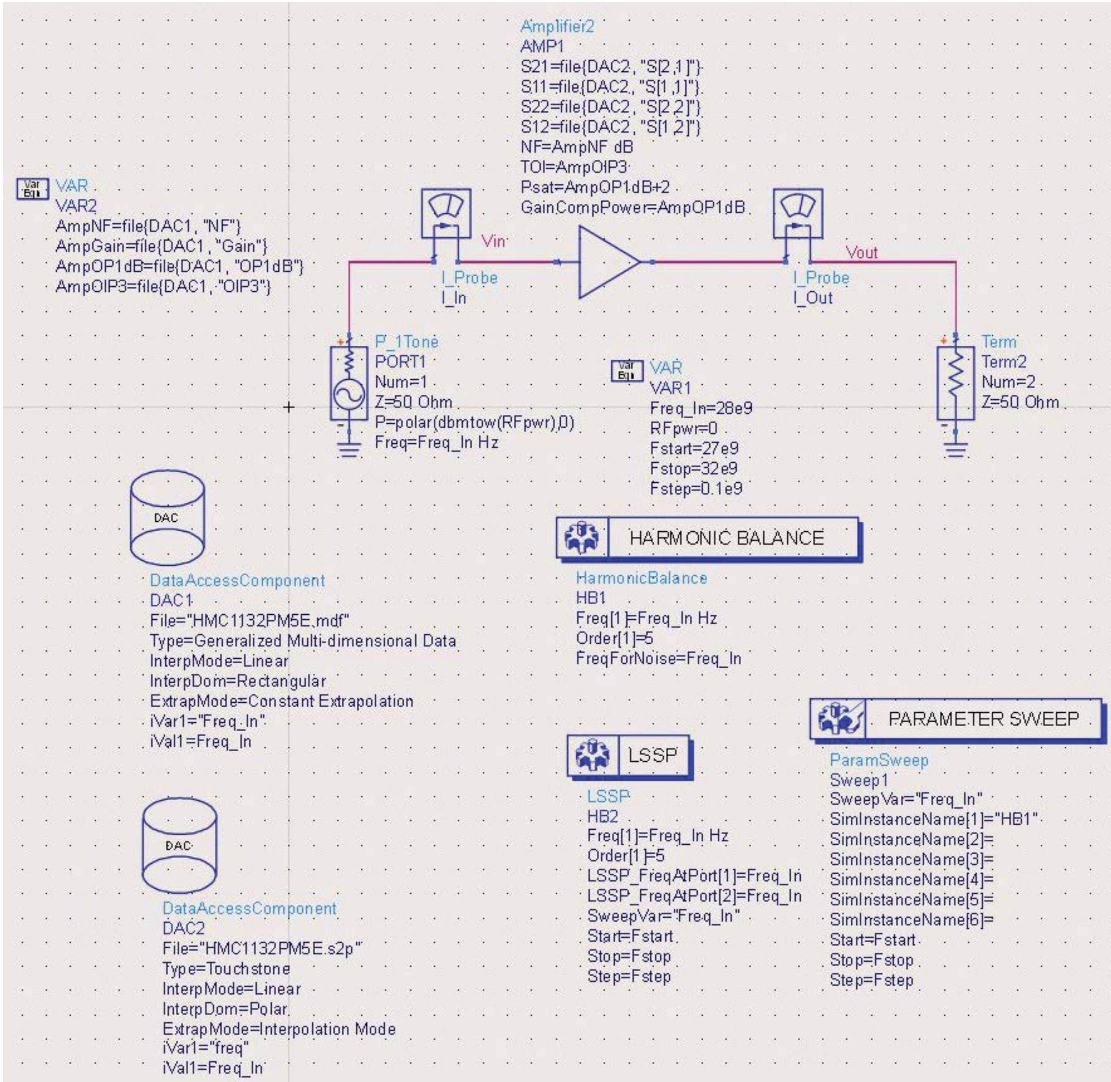

Figure 8. Using sys-parameter data in Keysight ADS using the Amplifier2 model.

References

PathWave System Design (SystemVue). Keysight Technologies, 2020.

PathWave RF Synthesis (Genesys). Keysight Technologies, 2020.

About the Author

Eamon Nash is an applications director for RF amplifiers and beamformers at Analog Devices. He has worked at Analog Devices for 30 years in various field and factory roles covering mixed-signal, precision, and RF products. He is currently focused on RF amplifiers and beamformer products for satcom and radar. He holds a Bachelor of Engineering (B.Eng.) degree in electronics from University of Limerick, Ireland, along with five patents. He can be reached at eamon.nash@analog.com.