VHDL-AMS Extensions Enable RF Harmonic Balance Simulation

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This frequency domain extension to VHDL-AMS gives an RF designer the ability to describe and analyze a wireless system from architecture to individual transistors on the RFIC

VHDL-AMS/FD is the extension language that supports harmonic balance simulation for frequency domain analysis. This frequency domain (FD) language extension provides the RF designer the capability to describe a wireless system from architecture to transistors. The use of harmonic balance overcomes both of the limitations found in the shooting or SpectreRF approaches. Neither different time constants nor complex frequency-dependent passive components impact the technique's ability to accurately solve circuit equations and provide meaningful results.

harmonic balance (HB) is most useful in the analysis of components or systems that involve intermodulation distortions (IMD) and/or frequency conversion. Examples include mixer IMD with closely spaced tones, power amplifiers, load-pull, frequency multipliers, steady-state response of oscillators, and system simulation.

Harmonic Balance

RFICs typically include frequency up-and/or down-conversions. HB is the ideal technique to analyze systems with multiple, closely spaced independent signals. Figure 1 is a circuit diagram of a classic mixer topology that requires accurate nonlinear analysis. Linear distributed models can be accurately modeled at the same time, because HB is a frequency-domain technique.

Nonlinear noise analysis is another unique capability of HB. Spice linear noise analysis cannot predict the noise performance of a circuit with frequency mixing effects or determine nonlinear responses to variations in input signal amplitude, such as gain compression. HB can accurately simulate nonlinear noise of mixers and oscillators, including their large-signal effects. This is guaranteed only if the initial point, X0, is close enough to the solution point. If not, different globalization strategies are helpful.

As usual, the described approach carries advantages and drawbacks that must be assessed. The ability of HB to obtain a steady-state solution is often mentioned among its main advantages. Another key advantage is its ability to handle any type of linear circuit, including black boxes with measured frequency responses. This includes elements with complex frequency-dependent behavior, such as microstrip lines, lines under layered substrates or under anisotropic substrates, and elements whose language points to a frequency-domain version of VHDL that is compatible with a harmonic balance simulator.

VHDL-FD Language

The advent of VHDL-AMS, which provides for the description of analog and mixed-signal models, has laid the foundation for an extension of that language into the frequency domain. This further extension is referred to as VHDL-FD. Referring to the VHDL-AMS *Language Reference Manual* (LRM), the VHDL language may be divided into digital and analog components, as well as a third circuit-descriptive component which handles either circuit decomposition into elements, or combines elements and circuit sub-blocks. This third component supports the construc-
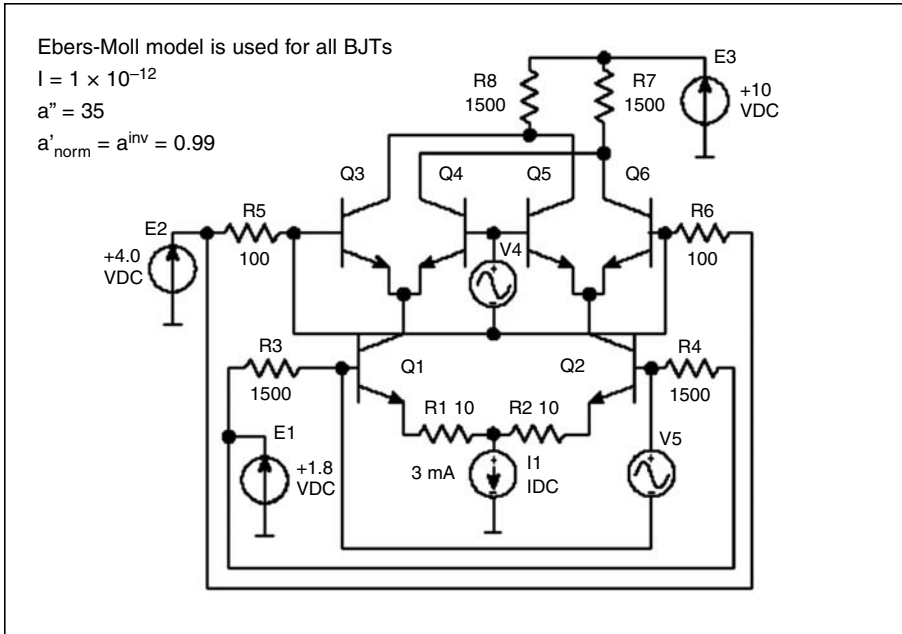
Figure 1 · A typical mixer schematic with voltage, current and signal sources identified for analysis.

tion ability of the language. For an analog circuit representation, VHDL-AMS uses two techniques: (1) basic-element representation and (2) low level (with respect to design hierarchy) equation-level representation. The equation-level representation builds a modeling basis for component-library design. A designer can build equations of any complexity, using different functions as needed. Figure lists the code used to define an amplifier for nonlinear analysis using HB.

The VHDL-AMS language supports the use of standard, physics-based equations along with branching "if" statements and procedural statements. Given the equation support, designers can build higher-level

```
entity nonlinear_amp is
generic (k1, k2, k3: real); port (quantity a_in, a_out : real);
end entity amp;
architecture eq of amp is
begin
a_in*k1+a_in**2*k2+a_in**3*k3==a_out; - nonlinear effects included
end architecture;
...
The example shows that the entity "nonlinear_amp" contains the parameters k1, k2, k3
The test bench for the amplifier is the following:
# amplifier jobs: - comment line
res1=HBparametric([3.e6,5,0.01,1000]) # - performs HB
print "================= results ================="
print res1; # - print res1 (complex structure)
print res1.getX("tout'reference") # - gets and prints only spectrum
print "================= tout.H1 =================".
print res1.getX("tout'reference",[1]) # of "tout'reference" variable
# - gets and prints only spectrum \
# of "tout'reference" variable at first harmonic
```

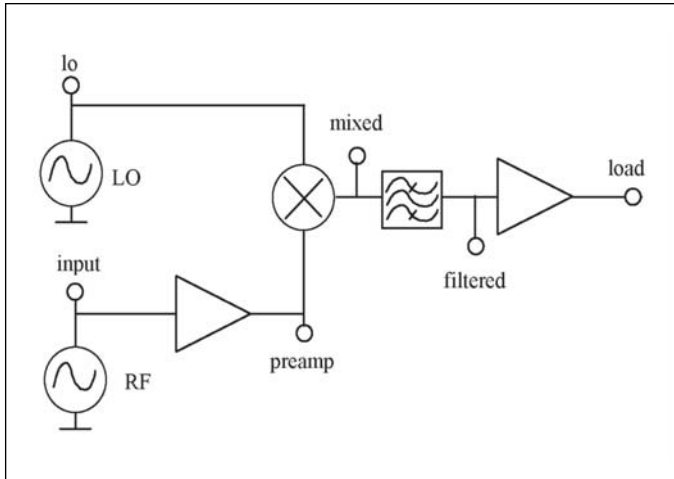**Figure 2 · Code for defining an amplifier using VHDL-FD.**

Figure 3 · Receiver front end to be analyzed using the VHDL-FD language and RINCON simulator.

Figure 4 · Spectrum plot of the receiver output with two-tone excitation.

blocks and connect them to create more complex structures. Two approaches are available for this: making connections using "quantities" and making connections through "terminals." Quantities are standard variables in the scope of VHDL-AMS. Several blocks can share the same variables, and connection via quantities. It is convenient to describe signal-flow diagrams and simple closed systems using quantities.

Terminals carry out additional work. They assume the preservation of conservation laws—such as Kirchoff's laws—in electrical engineering. Terminals contain two quantities: an "across" variable and a "through" variable. The "across" quantity acts like the voltage at a node or branch and the "through" quantity acts like the incident current of the node. Another useful feature of the behavioral approach is that it is multidisciplinary. It is possible to describe and simulate mixed systems, such as electromechanical, electrohydraulic, and laser systems, using this approach. These extremely useful characteristics provide a significant inducement to use VHDL-AMS as the basic language for adaptation in the microwave design realm, as a frequency domain form (VHDL-FD).

System Simulation

The receiver front end block diagram shown in Figure 3 illustrates the use of the VHDL-FD language and RINCON simulator to investigate system properties. Simulating this system under two-tone excitation gives us the spectrum shown in Figure 4 at the output.

The RINCON™ Simulator

The implementation of VHDL-AMS/FD is accomplished with the Ridgetop Group RINCON simulator. RINCON, based on C++, enables the design description from transistor to system. It supports multiple transistor
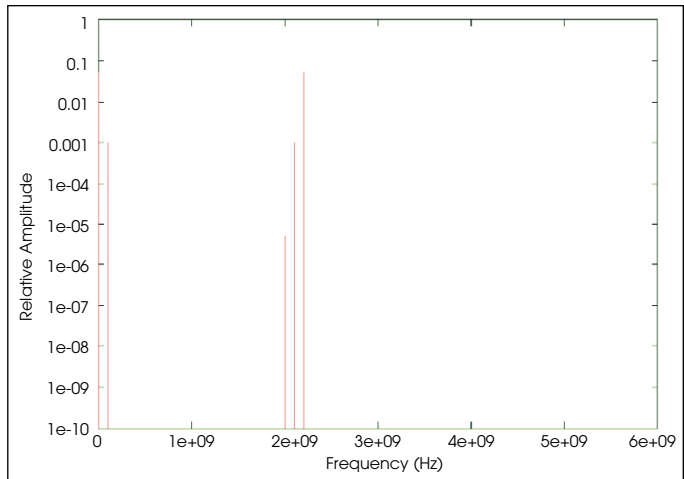
models and a library of over 25 RF/Mixed Signal elements (LNA, Filters, etc). To improve on the convergence of the system of equations, RINCON utilizes Krylov Subspace Solver and Modulation Harmonic Balance.

Krylov Subspace Solver

With the Newton-Raphson technique that HB simulators use, each iteration requires an inversion of the Jacobian matrix associated with the nonlinear system of equations. When the matrix is factored by direct methods, memory requirements climb as $O(H2)$, where H is the number of harmonics. An alternate approach to the solution of the linear system of equations associated with the Jacobian matrix is to use a Krylov subspace iterative method such as generalized minimum residual (GMRES). This method has a memory requirement proportional to $O(H)$, not $O(H2)$, in the context of harmonic balance. Thus the Krylov solver saves on memory requirements for large harmonic-balance problems, with a corresponding increase in computational speed. This speed makes it practical to use HB for full-chip simulation with multi-tone excitation.

Modulation Harmonic Balance

Modulation Harmonic Balance (MHB), also called envelope harmonic balance or signal envelope, is a simulation technique used by RINCON for microwave and RF components. It is typically used by communication systems to determine the behavior under complex modulated excitations.

The simulation cycle consists of an HB simulation, which determines regime before transient, and the sequence of MHB simulations at different time points. The signal domain is set to the quiescent domain during harmonic balance simulation and to time domain during

sequential MHB simulation.

The simulation sequence consists of setting up a domain signal in quiescent domain and then calling harmonic balance solver. After the domain is set to time domain, time is set to t_0 + t_step (where t_0 = initial time and t_step = default time step) and the following iterations are performed while current time is less than time limit: solve circuit at current time and advance time by step.

Currently, the same time step is used for all simulation cycles and is set up from outside along with the time limit.

Conclusion

Harmonic balance simulation is a well-known and frequently practiced design method for microwave and RF/Mixed Signal designs. The joining of VHDL-AMS with harmonic balance simulation technology finally enables the complete verification of the microwave and RF/Mixed Signal system.

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Ridgetop Group offers a wide range of basic models, called Templates, that are the basic building blocks, or behavioral models used with Rincon. The user can add parameters to these basic Templates and create specific, parameterized models that meet their requirements. The standard models available include:
- Resistor
- BJT Model
- Inductor
- Capacitor
- MOS Model
- MESFET
- GaAs FET
- SiGe FET
- Standard MOSFET
- BJT
- HEMT
- PIN Switch Diode
- Diode

Available Models in RINCON.