VHDL Approach Improves Nonlinear Simulation

A new approach to harmonic-balance simulation uses a frequency-domain-extended standardized modeling language to support the use of "black boxes" in simulations.

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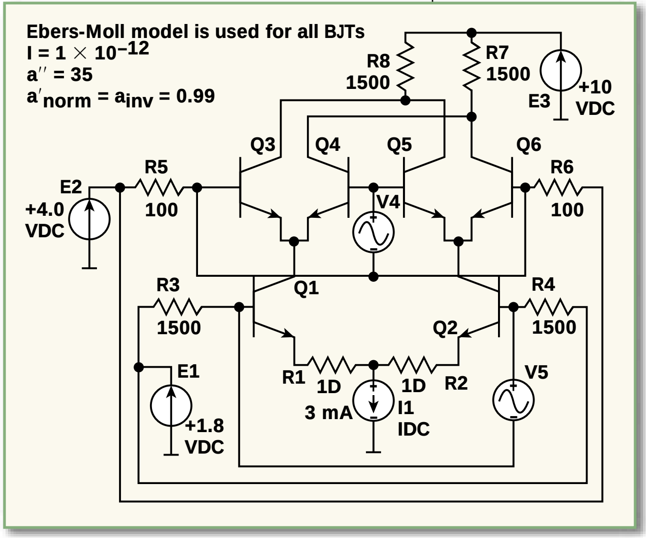
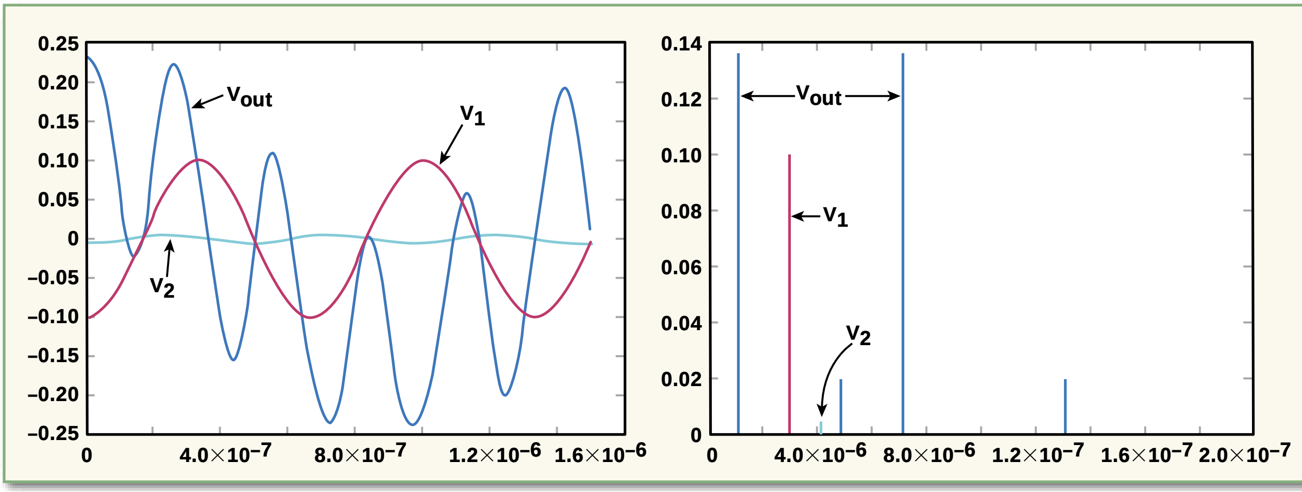
Microwave and RF designers have long sought higher levels of performance and accuracy in their simulation tools. Due to the special considerations in the microwave and RF region, there has been a complicated evolution ranging from the application of linear approaches of Touchstone and Simulation Program with Integrated-Circuit Emphasis (SPICE) simulations on nonlinear circuits to more advanced, up-to-date approaches, applying harmonic balance and complex time-domain techniques for fast simulation of nonlinear analog circuits. Fortunately, an approach has been developed to enhance the performance of harmonic-balance simulation through the use of extensions to standard very-high-definition-language (VHDL) models.

In the low-frequency area, the SPICE circuit description format is considered a de-facto standard. For high-frequency modeling (above approximately100 MHz), this has not been the case, however. The wide variety of RF and microwave elements has demanded more advanced description languages to accurately describe their behavior over varying conditions. To that end, most EDA suppliers created their own proprietary description languages to describe these components. However, it appeared to be a situation in need of standardization.



1. A Gilbert-cell mixer was chosen as the sample circuit for analysis in the new harmonic-balance simulator.

For modeling digital circuitry, proprietary and standards-based languages were created. The latest and most useful versions—VHDL and Verilog—entered the public domain and became widely used standards. Increasing demands for simulating complex analog, digital, and mixed digital ana-



2. In this simulation of the Gilbert-cell mixer, a high LO level of 100 mV was used.

log circuits led to development of extensions of these languages, VHDL-AMS and Verilog-AMS, although the microwave and RF simulation area remained without a standard description language. Fortunately, the use of extensions to a standard language, such as VHDL, may be able to accommodate the needs of microwave and RF design applications.

Apart from harmonic balance, a technique that simulates the circuit in the frequency domain, certain time-domain techniques are also useful for high-frequency simulations, although they carry certain limitations. These time-domain methods include Microwave SPICE, the shooting approach, and SpectreRF.

The use of SPICE (specifically,

$$F(X) \equiv L(\omega, \tau_i) \times X + N\left(X, j\omega X, e^{-j\omega\tau_i} X\right) + I = 0 \qquad (1)$$

Microwave SPICE) is perhaps the most traditional high-frequency modeling techniques and one of the oldest methods. This approach uses numerical integration of component equations and Kirchoff's laws in the time domain to create a solution for each time step. The time steps can then be graphed to examine the behavior of an overall circuit under various drive conditions. SPICE suffers from the usual drawbacks of time-domain techniques, including long computation times due to large time-constant differences found in microwave circuits, and an inability to handle transmission lines well, including the need for using lumped-element approximations and long computation times. Among the advantages of SPICE are the ability to solve simple circuits and the simplicity of the software itself. Most engineers are familiar with SPICE and can apply the software quickly.

A new technique using the shooting approach has also been introduced to deal with the differing time-constants issue.[1] The shooting approach eliminates excessive computations while a steady-state solution is being found. There is also an appropriate technique to find the transient response with different time constants present (such as with SpectreRF). These tools are adequate for their tasks, but the library of components with complex frequency dependency lacks. Both aforementioned techniques are suitable for ordinary differential equations (ODE) but not for equations with complex frequency-dependent components, which are not described by ODE.

The use of harmonic balance overcomes both 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.[2] Harmonic-balance equations usually are formulated by Eq. 1, where:

ω = the angular frequency in radians,

τ_i = the explicit delay component in circuit,

$L(\omega, \tau_i)$ = the complex linear operator, representing the linear part of the circuit,

X = complex spectrum of variables,

$j\omega X$ = the image of the variables' derivatives,

$e^{-j\omega\tau_I}X$ = the image of the delayed variable component,

$N(X, j\omega X, e^{-j\omega\tau_I}X)$ = the complex response of the nonlinear subcircuit, and

I = the vector of the free sources in the frequency domain (complex amplitudes).

Parameter X usually contains all of

the necessary frequency components (fundamental and harmonic components with orders from 5 to 20).

Most complex calculations are contained in the N term of Eq. 1. There is no closed-form formula to calculate response of the nonlinear elements in frequency domain, excluding only some special cases (e.g., polynomials). To deal with this, frequency-transformation techniques are applied.

With frequency-transformation techniques, the response Fast Fourier transform (FFT) is typically used. First, the time-domain waveform of the stimulus is computed through an inverse FFT. Then, its time-domain response is computed using nonlinear functions of element(s), and its frequency-domain response is calculated through the forward FFT. Multidimensional FFTs are used to enable transformation of quasi-periodic waveforms.

The Newton method is used to solve the harmonic-balance equation. Modern implementations use modifications that provide the capability to handle large and complex systems. The Krylov subspace approach is an example of this.[3]

To simplify a depiction of its function, assume that the usual Newton method is applied. Then, according to Eq. 1, the sequence of steps is:

$$X_{i+1} = X_i + k_i \times S_i \qquad (2)$$

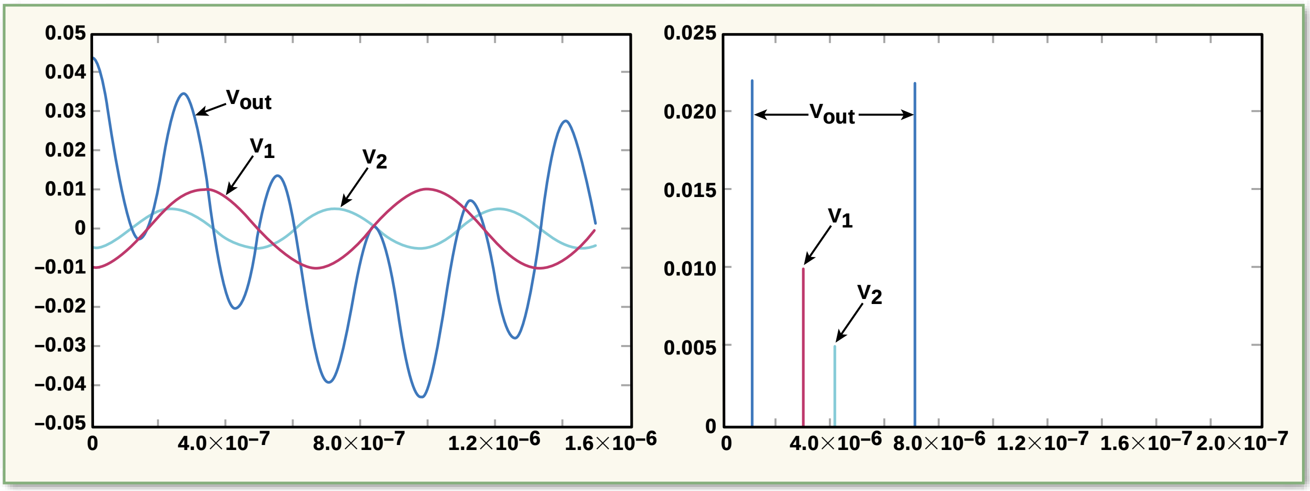
$$Si = -J_i^{-1} F_i$$

$$J = \frac{dF}{dX} \qquad (3)$$

which should converge to the solution of Eq. 1.

This is guaranteed only if the initial point, X_0, is close enough to the solution point.[4] If not, different globalization strategies are helpful.[5] Usually it consists of choosing proper value of k_i to allow Eq. 2 to converge to a solution, where F = 0.

As usual, the described approach carries advantages and drawbacks that must be assessed. The ability of harmonic balance to obtain a steady-state solution is often mentioned among its main advantages. This follows directly from the formulation of Eq. 1. Another key advantage is its ability to handle circuits of any linear circuit, including black boxes with measured frequency responses. Referring to the term $L(\omega, \tau_i)X$ in Eq. 1, L can represent any possible linear transformation of X in the complex plane, so any imaginable linear circuit (as long as Kirchoff's laws are satisfied at its ports) may be represented by L. This includes elements with complex frequency-dependent behavior, such as microstrip lines, lines under layered substrates, under anisotropic substrates,



3. In this simulation of the Gilbert-cell mixer, a low LO level of 5 mV was used.

and others. Using the multidimensional FFT in harmonic balance supports the solution of circuits under quasi-periodic excitation, so different time constants are not an issue.

The main disadvantage of harmonic balance is the large computational time needed to provide a solution. The harmonic-balance task has an approximate cubic algorithm complexity, which is defined as a "bottleneck" of the algorithm (solving Eq. 3 to define the step). Another time-consuming procedure is calculating the response of the nonlinear subcircuit term N in Eq. 1. It requires many nonlinear function calculations, along with forward and reverse FFT. Harmonic-balance-based envelope techniques,[6] mixed shooting/time-integration schemes such as in Spectre RF, and/or direct time-domain integration are more suitable.

The need for microwave and RF engineers to have a standard description language points to a frequency-domain version of VHDL that is compatible with a harmonic-balance simulator. With the advent of VHDL-AMS, which provides for the description of analog and mixed-signal models, the foundation has been laid 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),[7] VHDL language may be divided into digital and analog components, as well as a third circuit-descriptive component, which handles circuit decomposition into elements or vice-versa (combining elements and circuit sub blocks). This third component supports the construction ability of the language.

The digital component is implemented using signals, processes, and the methods for their interconnections: concurrent statements and sequential statements. The analog component is implemented through quantities, terminals (such as the special case of structure of quantities with conservation semantics), and simultaneous statements. The descriptive component is represented by a component-instantiation statement and serves as the infrastructure of the language for describing the topology of a circuit.

For an analog circuit representation, VHDL-AMS uses two techniques: basic-element representation and 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 functions as needed. 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 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 facilitates this. It is convenient to describe signal-flow diagrams and simple closed systems using quantities.

Terminals carry out additional work—they assume 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 similar to 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 and electrohydraulic systems, using this approach. These extremely useful characteristics provide a significant inducement to use VHDL-AMS as the basis language for adaptation in the microwave-design realm, as a frequency-domain form (VHDL-FD).

Consider the classes of circuits that may be represented through this analogous subset of VHDL-AMS. The following items can be used in equations as part of the language:

• Variables (or quantities, using the terminology of VHDL-AMS).

• Derivatives of variables (which are mapped onto 'DOT attribute).

• Integrals of variables ('INTEG attribute).

• Delayed values of variables ('DELAYED attribute).

These values may be combined through algebraic functions to form the equations. This mechanism creates the ability to express any system of differential-algebraic-equation (DAE) sets when modeling. In terms of circuit simulations, this is equivalent to incorporating nonlinear and common linear-reactive elements, such as inductors and capacitors. Since the methods for modeling of distributed systems are not yet available with VHDL-FD, except as lumped-circuit approximations, it will be necessary to create the necessary extensions to accommodate frequency-domain modeling capabilities that have distributed reactive elements.

The high-frequency, extremely linear parts of microwave circuits are best described in the frequency domain, while the nonlinear parts are best modeled in the time domain. Thus, the microwave-design tool should be able to describe a model in the frequency domain. However, while not precluded, it is not an initial VHDL objective.[7]

To enable frequency-domain modeling, it is necessary to operate with quantities in the frequency-domain and time-domain together in one module. Thus, a frequency-domain extension is proposed to accommodate this need for handling quantities with VHDL in both domains. Under this scenario, an extended description capability is:

$$ui'FD = Zk(frequency) \times iinFD \quad (4)$$

where:

ui'FD and iin'FD = the images of ui and iin in the frequency domain (complex values) and

Zk(frequency) = some complex value of (frequency-dependent) impedance.

This notion enables the use of fre-

(Continued on page 102)

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quency-domain modeling. If the model in the time domain is described as:

$$i = C \times v'dot \qquad (5)$$

It may be simply and automatically transformed into frequency-domain—see Eq. 6 on page 102

The time-domain model can be simply represented in the time-domain as well, but many complex frequency-domain models (e.g., with dispersion) have a very complex time-domain description. Using frequency-domain extensions, such as that shown in Eq. 6, it is possible to extend the modeling capabilities of VHDL-AMS to high-frequency bands.

Ridgetop Group (Tucson, AZ) has created a working simulator, Rincon™, that employs the VHDL-FD extensions with a harmonic-balance simulator **(see table).** The simulator can be demonstrated through the analysis of a Gilbert-cell mixer **(Fig. 1)**. **Figure 2** shows the simulation results when using a high local-oscillator (LO) level of 100 mV, while **Fig. 3** shows the simulation results using a lower LO level of 5 mV. **MRF**

$$i'FD = C \times math\_j \times math\_2\_pi \times FREQUENCY \times v'FD \qquad (6)$$

Comparing different simulation and modeling techniques

SIMULATOR TYPE	RELATIVE COMPUTATION TIME	ACCURACY	MODEL LIBRARY	NEW MODELING CAPABILITY	COMMENTS
Harmonic balance	Average	Excellent	Proprietary	Limited	Model limitations
Rincon™ Simulator–harmonic balance with VHDL-FD modeling capabilities	Average	Excellent	Open	Extensive	Newly introduced
SPICE	Long	Poor	SPICE primitives	None	Widely understood
SpectreRF	Short	Medium	Proprietary	None	Limited library

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