

# Extended Frequency-Domain Modeling Capabilities for VHDL-AMS

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## ABSTRACT

This paper presents frequency domain modeling extensions for an analog VHDL-AMS subset in the scope of Harmonic Balance simulation. Proposed extensions cover practical applications for both linear and nonlinear frequency-domain modeling. The proposed approach is implemented in Harmonic Balance simulation software but could be applied to other frequency domain simulators as well.

## 1. INTRODUCTION

During recent years substantial efforts have been spent in the field of developing hardware description languages (HDLs). For digital circuit simulation, progress has been achieved with the development and application of VHDL and Verilog HDLs. In the analog realm, the situation has been different. SPICE is the standard tool for analog simulation, and a variety of SPICE dialects and model sets have been developed. In addition, there are proprietary languages for specialized RF and microwave description purposes. The variety of formats has made the work of circuit designers more difficult, as no single simulator provides all of the necessary features and analyses. Designers often need to switch from one tool to another to achieve design goals. Worse yet, simulators sharing a somewhat common language (e.g. SPICE-like) have different device models, which makes it harder to compare simulation results.

To overcome these issues, two analog HDLs have been developed as a standard – VHDL-AMS [9] and Verilog-A. That is an important achievement, as opens the way for the standardization of device libraries and development of model exchange [3]. Both languages are defined as languages for time-domain modeling. Neither language supports frequency domain simulation, required by most RF and microwave design tasks. Substantial efforts are made to develop standard for MMIC HDL – MHDL [5].

This paper describes VHDL-AMS extensions to provide advantages of frequency-domain modeling and simulation.

This work is an extension and refinement of results published earlier in [6].

## 2. HARMONIC BALANCE TECHNIQUE

Continuous (analog) circuit equation may be formulated as:

$$i(v(t)) + \frac{dq(v(t))}{dt} + \int_{-\infty}^t y(t-\tau)v(\tau)d\tau + u(t) = 0 \quad (1)$$

or

$$f(v, t) = 0 \quad (2)$$

where  $v(t)$ ,  $u(t)$ ,  $y(t)$ ,  $i(v(t))$ ,  $q(v(t))$  and  $f(v, t) \in R^N$ ,  $V(t)$  and  $u(t)$  are assumed to be T-periodic,  $y(t)$  is linear response of linear subcircuit and  $i(v)$  and  $q(v)$  are only nonlinear members.

Considering both  $v$  and  $f$  for (2) as Fourier series and making necessary transformations, Harmonic Balance (HB) equations may be written as the following:

$$F(V) = I(V) + \Omega Q(V) + YV + U = 0 \quad (3)$$

where  $F(V), I(V), Q(V), V, U \in C^{(K+1)N}$ ,  $K$  number of considered frequencies,  $Y, \Omega$  are square block matrices:

$$\Omega_{nn} = \text{diag}\{0, \dots, j\omega_n, \dots, j\omega_K\} \quad (4)$$

$$Y_{nn} = \text{diag}\{Y(0), \dots, Y(\omega_n), \dots\}. \quad (5)$$

As most nonlinearities are modeled in time domain, the first two terms of (3) are usually computed in the time domain using Fast Fourier Transformations (FFT):

$$I(V) = \Phi\{i(\Phi^{-1}\{V\})\} \quad (6)$$

(3) is solved usually by exact or inexact Newton method [1,2].

### 3. FREQUENCY-DOMAIN MODELING

As VHDL-AMS is defined in time domain entirely, it does not contain the means to define behavior in the frequency-domain. Many circuits at microwave and RF frequencies show complex frequency-dependent behavior that is difficult to model solely in the time domain.

To extend language capabilities, an existing language feature is used – Attribute. Attribute is a property of quantity; for example, if some quantity Q is defined, then it possible to define attributed quantity Q'·dot to refer to time derivative of that quantity, and Q'integ refers to integral of quantity Q. Attribute may have argument(s), for example Q'delayed(10ns) defines delayed quantity to 10 ns.

We will consider two proposed features – attributes for linear and nonlinear frequency-domain modeling.

#### 3.1 Linear Modeling

Let quantities I\_c and U\_c to be defined respectively as current through and voltage across a capacitor. Then attributed quantities I\_c'FD and U\_c'FD will represent spectrum of ic and uc respectively and may be used in equations:

$$I_c'FD = 2 \cdot \text{math}_j \cdot \text{math}_p \cdot \text{FREQUENCY} \cdot C \cdot U_c'FD;$$

FREQUENCY here is predefined language function returning the value of the current frequency.

More generally:

$$x'FD = \text{func}(\text{FREQUENCY}, a, b, c) \cdot y'FD;$$

where func ( ) is user defined.

Similarly, circuit impedance or admittance values may be calculated during simulation or picked up from an external source such as a file or complex database.

It is assumed that any statement representing an equation that uses a quantity with the attribute 'FD is defined in frequency domain too, so it is impossible to mix domains inside one statement.

This extension correspondents to the third term of (3) and broadens the class of described circuits, including distributed parameters circuits and other linear circuits, which may be described in frequency domain.

#### 3.2 Nonlinear Modeling

In contrast to linear case, the nonlinear case is dependent on frequency conversion, when excited into frequencies that result in interaction with other frequencies..

For Harmonic Balance purposes, time domain models are typically used. They are represented as the first two terms of (1) and (3) respectively, and the are calculated using (6). But very often time domain modeling is unnatural. For example, there is the case of RF behavioral modeling, when a mixer is defined by its conversion quotient directly in frequency domain.

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#### Listing\_1. Transmission line model using VHDL-AMS with frequency-domain extensions

---

```
entity tline is
  generic (z0, f0, teta0: real);
  port (terminal a,b: electrical);
end entity tline;
architecture eq of tline is
  quantity u1 across i1 through a;
  quantity u2 across i2 through b;
  constant teta: real:=2* $\pi$ *teta0/f0;
begin
  if (FREQUENCY() = 0) use -- DC
    i1'FD==1000*(u1'FD-u2'FD);
    i2'FD==1000*(u1'FD+u2'FD);
  else -- RF
    i1'FD==1./z0* COMPLEX(0, -1/tan(teta*FREQUENCY())) *
      (u1'FD-./cos(teta*FREQUENCY())*u2'FD);
    i2'FD==1./z0* COMPLEX(0, -1/tan(teta*FREQUENCY())) *
      (-1./cos(teta*FREQUENCY())*u1'FD+u2'FD);
  end use;
end architecture;
```

---

An interesting option for frequency-domain modeling is the use of describing functions [7,8]. This approach allows us to represent relation (6) in simplified form of:

$$I^k (V^m) = G^k (X^0, X^1, X^2, X^3, \dots, X^m) \quad (7)$$

where the superscript is the harmonic number. There are some limitations of the form of G(), which are explained in [8], that restrict the choice of G(), but no way related to their representation in language.

To model nonlinear behavior, an additional attribute 'H() is proposed. 'H() may have one or more indices, corresponding to harmonic number. For example, if Q is some quantity, then Q'H(0) represents the DC component of Q, Q'H(1) is the fundamental frequency, and so on.

Thus, one may define behavior of power amplifier as:

$$\begin{aligned} v\_out'H(1) &= F1(v\_in'H(1)); \\ v\_out'H(2) &= F2(v\_in'H(1)); \\ v\_out'H(3) &= F3(v\_in'H(1)); \end{aligned}$$

where F1(), F2() and F3() are user-defined describing functions.

Such an approach may be extended (allowing multidimensional H() indices) onto the case of many excitations. For example, for some mixer:

$$\begin{aligned} v\_out'H(1,-1) &= F1(v\_in'H(0,1)); \\ v\_out'H(2,-1) &= F2(v\_in'H(0,1)); \\ v\_out'H(3,-1) &= F3(v\_in'H(0,1)); \end{aligned}$$

where index (0,1) is related to RF, (1,0) – to LO, (1, -1) – to RF, etc.

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**Listing 2. Behavioral model of amplifier.**

```

entity amp is
  generic (k1, k2: real);
  port (port inp, outp: real);
end entity amp;
architecture behav of amp is
begin
  a: procedural is
    variable am, fi: real;
    begin
      am:=abs(inp'H(1));
      fi:=angle(inp'H(1));
      outp'H(1):=(k1+3*k2*am*am)*inp'H(1);
      outp'H(3):=(k3*am*am*am)*exp(math_j^3*fi);
    end procedural;
  end architecture;

```

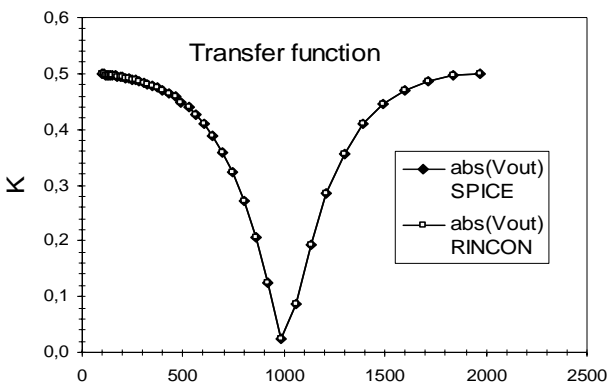
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#### 4. IMPLEMENTATION AND SIMULATION RESULTS

The proposed approach is implemented in Harmonic Balance simulation software Rincon [5] that uses a VHDL-AMS input language. To demonstrate the proposed capabilities, two different examples are considered. Linear modeling is demonstrated using a simple transmission line model. Nonlinear modeling is demonstrated using a behavioral model of an amplifier. The amplifier model takes into account nonlinearities such as gain compression and 3<sup>rd</sup> harmonic generation.

A VHDL-AMS model of transmission line is shown in Listing 1 and the simulation results are shown in Figure 2.

A behavioral VHDL-AMS model of an amplifier is presented in Listing 3. The behavioral model is built in accordance with the cubic impairment model and takes into account generation of the fundamental frequency and third harmonic only. It is possible to show, that cubic nonlinearity  $f(x) = k_1x(t) + k_2x(t)^3$  under sinusoid excitation:



**Figure 1. Response of simulated circuit with transmission line.**

$$x(t) = A \cdot [ e^{j\varphi} e^{j\omega t} + e^{-j\varphi} e^{-j\omega t} ] \quad (8)$$

will react as:

$$f(x(t)) = (k_1A + 3k_3A^3) [ e^{j\varphi} e^{j\omega t} + e^{-j\varphi} e^{-j\omega t} ] + (k_3A^3) [ e^{j3\varphi} e^{j3\omega t} + e^{-j3\varphi} e^{-j3\omega t} ] \quad (9)$$

That relation (9) may be used as the behavior model for the amplifier with nonlinear signal impairments. Behavioral modeling has the additional benefit of running the simulation more quickly, as it is an abstraction of the circuit-level model.

#### 5. CONCLUSIONS

A VHDL-AMS subset suitable for RF analog circuit simulation by Harmonic Balance technique is described along with possible Frequency-Domain modeling extensions. The approach described gives increasing flexibility in RF and microwave component modeling and broadens the class of tasks to be described by language. That set of functions is called VHDL-AMS/FD and used in Rincon RF circuit simulator [4].

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