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## 1 Introduction

This deliverable is related to a distortion contribution analysis algorithm called Volterra on Harmonic Balance (VoHB) [1, 2]. It breaks the total nonlinear distortion given by harmonic balance to a vector sum of smaller components so that the dominant causes, mixing and cancelling mechanisms can be easily seen.

The operation of VoHB analysis has already been described in the ICESTARS deliverables D2.8 and D2.9, as well as in publications [1, 2]. To summarise, it uses harmonic balance simulation to fit and replace every nonlinear VCCS (voltage-controlled current source) by a multidimensional polynomial, and then uses the polynomial model to calculate the contributions of band-to-band mixing. As in traditional Volterra analysis, a linear AC analysis is used to calculate the transfer gain of a given distortion tone from the origin of nonlinearity (one VCCS) to a chosen point in the circuit.

At the starting of the project, the prototype implementation of the algorithm operated only for single-device circuits, and only for two partially opened device models. The reason for this was that the prototype was built on top of the APLAC simulator, without information about the device-to-device transfer functions or internal structure of any other models than the two chosen models, whose general internal structure, node voltages and branch currents were open for probing.

## 2 Requirements and constraints

The main requirements and constraints for implementing the current version of the analysis were:

- To make the analysis general, access to all nonlinear sources within all device models is needed
- Linear AC analysis matrix at all distortion frequencies is needed to solve the transfer gain from distortion sources to any output point.
- Information about the model hierarchy is needed – for example, if a BJT base capacitance  $C_{pi}$  is causing distortion, we need to be able to plot to what device it belongs to (e.g. in format X1.Q1.Cpi)
- As device models contain a lot of code and editing them is prone to errors, it would be highly desirable to minimise the changes needed in device models themselves.
- Juridical problems complicate joint development, as companies usually don't want to pass their source code to anybody.

### **3 Outline of the implementation**

The actual implementation of a generic multi-device VoHB simulator was actually easier than expected, thanks to a few unique basic characteristics of APLAC simulator core and interface development help by staff from AWR-Aplac and TKK-AALTO. The key elements to this success are described next.

#### **3.1 VCCS based modeling of APLAC**

A huge simplification of the task was caused by the fact that APLAC describes circuits in an object-oriented way where all circuits and devices are inherently broken down to VCCS (voltage controlled current sources) elements with one or more control voltages – and this is exactly the form needed for VoHB analysis. A consequence of this is that now the analysis can be built directly at VCCS level, i.e. below the device model level, and hence avoiding any changes in the existing device models. This way of implementation makes the analysis automatically available for all existing and future device models, as long as these follow the general strategy of APLAC of breaking everything down to VCCS elements.

A further consequence of the object-oriented structure of APLAC modelling is that it automatically maintains parent-child relationships, so that every VCCS can easily be connected to its parent device and subcircuit. In addition linear and nonlinear VCCS's are treated separately, which eases the tracking of the VCCS's to be fitted.

#### **3.2 AIF interface**

AWR-APLAC and TKK built an interface that allowed us to write own C code and use some chosen APLAC-internal functions and data structures. This functionality was implemented in application interface AIF that currently allows e.g. the following operations:

- Accessing input voltages and output currents of VCCS simulated using HB. This is needed for fitting the polynomial nonlinear models.
- Filling and adding components and component values in the device matrix.
- Running HB and AC analyses with given parameters.
- Drive (or sample) a selected VCCS with any kind of input using HB (maintaining the order of the analysis and using the existing tones). This can be used to reduce the correlation of driving signals in some hard-to-fit multi-port VCCS. This is discussed in more detail in section 5.
- Running many other APLAC-internal functions.

While AIF is well suited for this kind of joint development, it still reveals some details of the simulators internal data (for example, the structure of the device models). Hence, it will most probably not be publicly available.

## **4 ... and some complications**

Despite the quick progress enabled by inherent VCCS based modeling and the AIF interface, some partially surprising problems still emerged, and caused some additional coding. As these effects are expected to be common to most simulators, they are listed here.

### **4.1 Calculation of the VCCS current**

In normal HB simulation, the solution consists of vector of node voltages, and branch currents that are used to fill and iterate KCL equations. Branch currents are normally not measured or stored, but the polynomial fitting used in VoHB requires that both the controlling voltage and output current spectra are available. Hence, after the solution of the node voltages, one additional evaluation of the VCCS sources' I-V functions was needed to calculate and store the output current spectrum of each nonlinear source.

### **4.2 Multi-input VCCS**

In the earlier prototype implementation of VoHB, one, two, and three-input polynomial sources were used and fitted. While debugging the current implementation, it appeared that in most device models quite many of the VCCS elements had more than three input voltages. Not all of them are really affecting the source, but are a result of the form of the function used to evaluate the source: often, several input signals are used to calculate a couple of circuit parameters at the same time. In such a case, say, two of five input signals may affect one VCCS, and the remaining ones the other one.

The multitude of input signals may cause erroneous results, when the VCCS is fitted using data that is not really affecting its operation. One quick way to eliminate excess control signals was found by checking the partial derivatives of the currents: if the partial derivative with respect to the studied voltage is zero (or very small), no polynomial coefficients are fitted for that control voltage. This helped to minimise the number of inputs to those that are really significant.

Another problem is related to the fact the analysis itself does not use any information of the model structure, but we have to rely that the source names originally given to the model-internal VCCS are meaningful to the user. Also many of the control signals are voltages of internal nodes of the device model, and hence not exactly same nodes as

device gate and drain nodes, for example. Also, the order of the input voltages may vary in function calls, making it difficult to track what input is related to gate or drain, for example. This problem was partially solved so that the input signals were sorted by their relative strength, so that the dominant control (typically related to base or gate voltage) is treated first, and the remaining in descending order. This is also used to adjust the model order: the highest order polynomial is given to the most dominant input, while the order of the less significant inputs can be reduced.

## 5 Further aids for the polynomial fitting

Deliverable D2.9 concentrated much on the numerical problems of fitting a multi-input polynomial source, where the higher order spectra correlate strongly. For example, a Chebychev type expansion was used to break down the correlation of higher order spectra.

One thing that can not be solved by scaling or by different series expansion is the fact that the different control signals really correlate – this happens naturally e.g. in the gm element of a quite linear amplifier. In such a case, the fitting matrix will be close to singular, and the fitted polynomial coefficients may be unreliable.

To avoid this problem, the previous approach was to add an orthogonal test signal in the output of the amplifier (see Fig. 1), but this can not be easily done in a multi-device, multi-stage amplifier, for example. Instead, a method for independent characterisation of each VCCS was built.

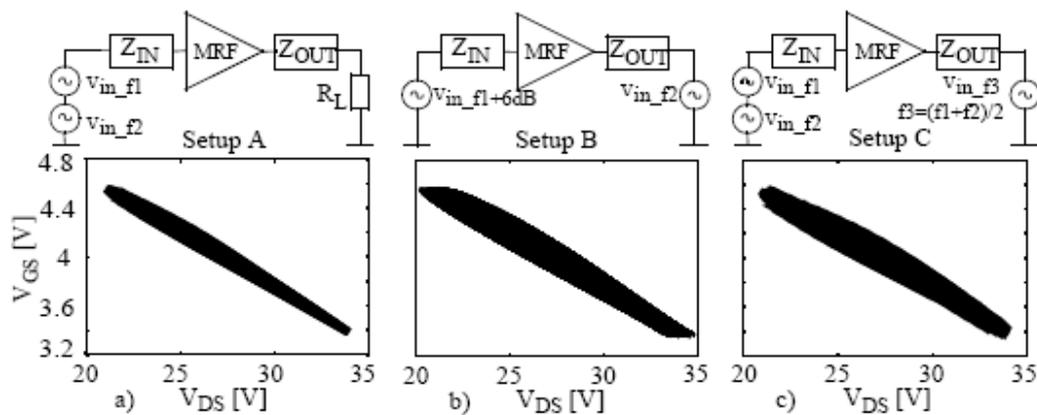


Figure 1. Vgs-Vds correlation in an LDMOS amplifier driven by a) a normal 2-tone test, b) a 1-tone input, 1-tone output test, c) a 2-tone input – 1-tone output test. [3]

The new fitting procedure (called frequency sampling) operates as follows:

- first, a harmonic balance simulation is run to record the signal amplitudes or trajectories around the VCCS elements
- if VCCS control signals correlate badly (this can be verified e.g. by calculating the condition number of the fitting matrix), the spectral content of the inputs can be changed by modifying the amplitudes of the existing tones
- so far the best technique seems to be to add such a tone that adds a low-frequency beat signal, broadens the signal trajectory, but does not considerably increase the maximum amplitude.

Various combinations of tones were tested, concentrating on small output-of-band signals. As an example, the original highly correlating VGS-VDS trajectory is presented in Fig. 2 a). It can be seen that the trajectory is very narrow, as VGS and VDS correlate strongly. In Fig. 2 b)-c) the 15 Vpp VDS voltage is modified by adding a  $4V \angle 90^\circ$  to the envelope tone, to the 2nd-harmonic tone and to both, respectively. It can be seen in each case, that the condition number is reduced significantly as the data trajectory has widened.

Care is needed in modifying the inputs, though. In the above example, the average accuracy of the output current spectrum of the polynomial model decreases 6-12 percent units. This is a symptom of characterising the VCCS under different conditions where it is actually used – in short, the output peak-to-peak amplitude increases too much when adding the new excitations. In the current implementation of this frequency sampling procedure the amplitude and phase at envelope, 2<sup>nd</sup> and 3<sup>rd</sup> harmonics are searched for strongly correlating VCCSs by minimizing the condition number, average and standard deviation of the fitting accuracy. In practise, one also needs to limit the excess signal amplitude so that the VCCS still operates in the same region of operation. This can be tracked from the relative strength of the harmonics, and 5-10% increase in overall peak-to-peak amplitude can serve as a safe starting point.

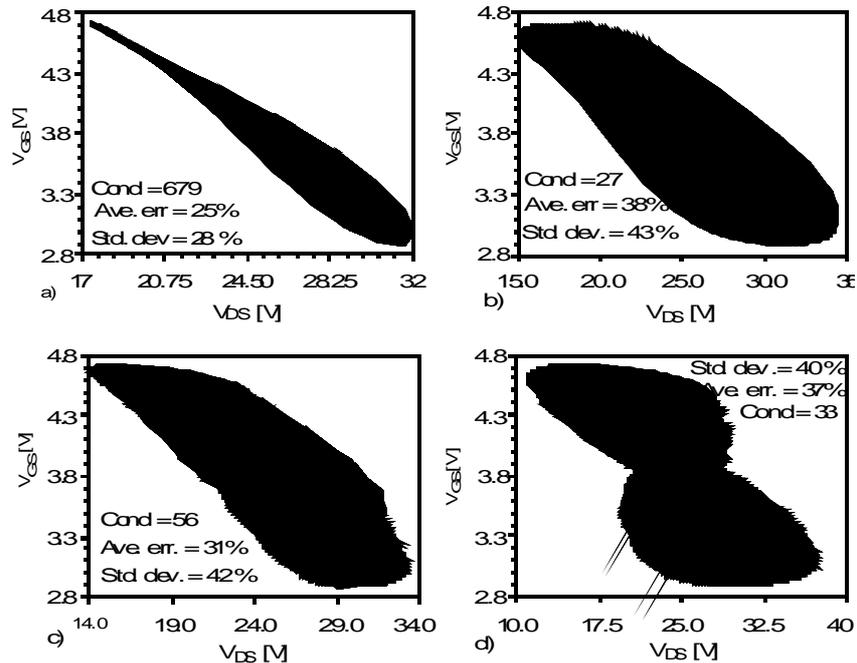


Figure 2  $V_{GS}$ - $V_{DS}$  swing of a) normal control voltage,  $4\angle 90^\circ$  added to b) envelope tone, c) 2nd harmonic tone, d) both tones of  $V_{DS}$

The cost of this per device frequency sampling and fitting is increasing simulation time. Hence, it is applied only when a VCCS has several controlling inputs that are really affecting the output currents of the VCCS and if the condition number of the polynomial fitting matrix is high enough.

## 6 Validation results

### 6.1 *transAmp LNA results*

In order to test the VoHB technique in multidevice analysis the transAmp test circuit provided by Qimonda was set up in APLAC. The transAmp circuit includes two NMOS device modeled by BSIM3 model that has not been used in VoHB before – also, this circuit is a (minimal) multi-device circuit. In the first case the 2-tone input signal close to compression (-15 dBm) was applied to the transAmp circuit and the response at the node Output was observed. The total IM3 distortion at the output of each nonlinear VCCS is shown as a vector plot in Fig. 3. It can be seen that the  $I_{ds}$  of Q2 transistor (the input NMOS) is causing most of the IM3, while Q2.Qgate (CGS) is the second largest contribution. The polynomial approximation agrees with HB within 5.4 % which is good considering that the device is almost in the compression region. The simulation time is around 800ms.

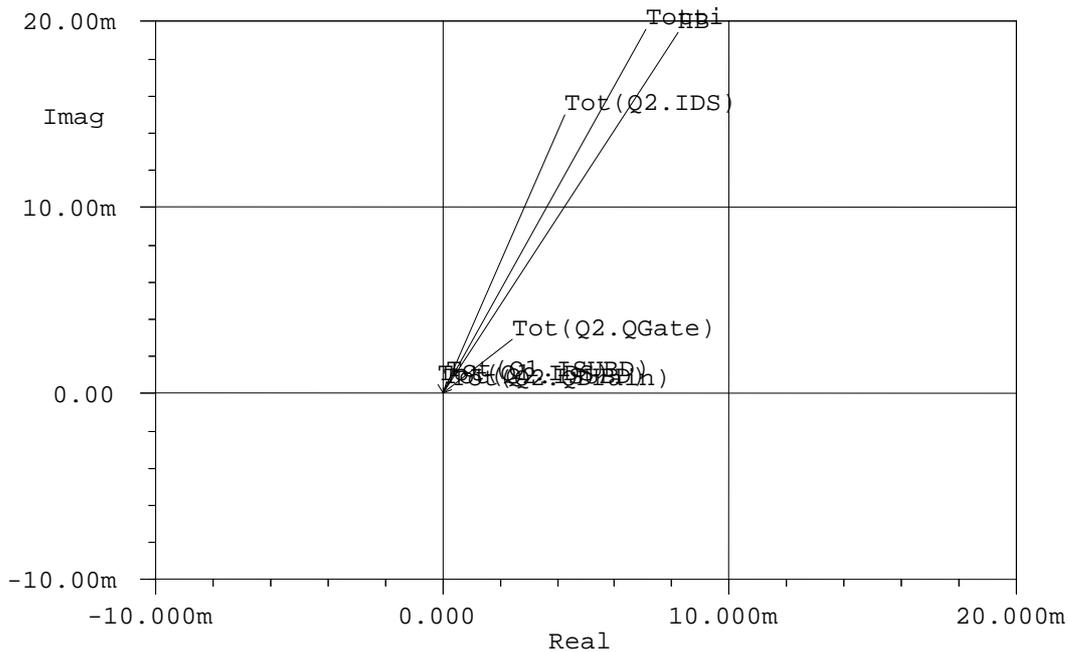


Fig. 3 The total IM3 distortion of each nonlinear VCCS at the Output node.

The more detailed view of IM3 generated by the IDS source of Q2 device is presented in Fig. 4. It shows that IM3 is caused by a strong cubic nonlinearity of the 2<sup>nd</sup> controlling input (V(K030V030)) and a very large contribution that is mixed from baseband to the fundamental band via quadratic input nonlinearity (V(K020M01)). In addition, the distortion mixed to fundamental band from 2nd harmonic band (V(K020M12)) is rather strong. The notations used show the form of the polynomial nonlinearity (e.g. K020 means quadratic form in the 2<sup>nd</sup> input or gate) and the mixing harmonic bands (0=DC, 1=fundamental, 2= 2<sup>nd</sup> harmonic, and so on).

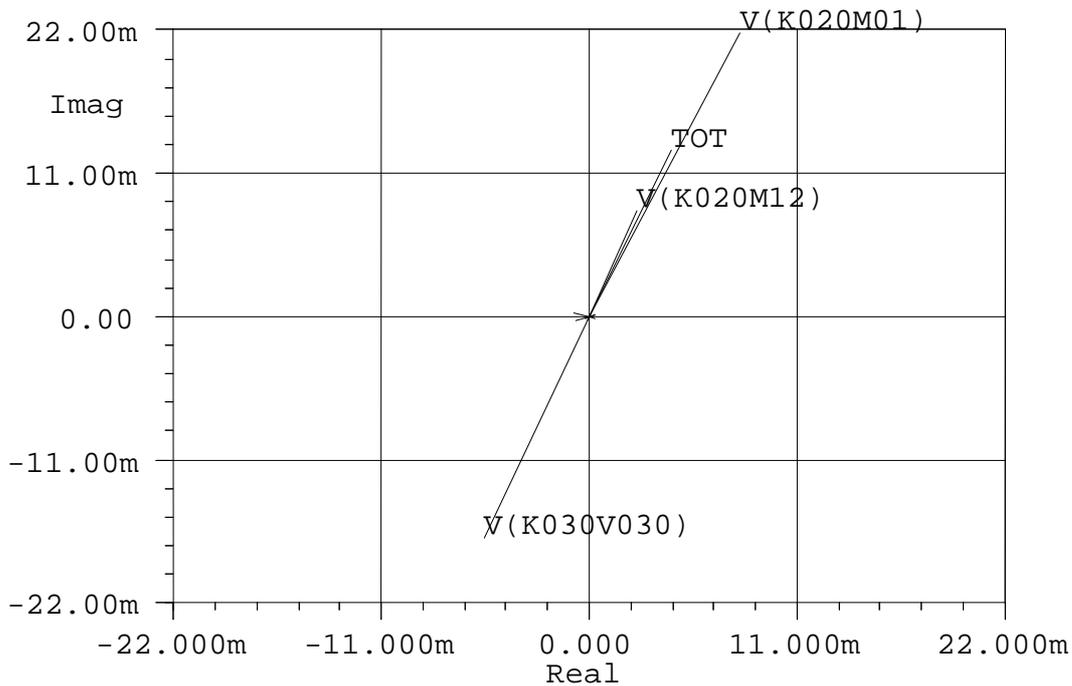


Fig. 4 The IM3 contributions of I<sub>bs</sub> source of Q2 at the Output node

## 6.2 Other test structures

Several other test circuits of the VoHB analysis have been built for verification, debugging, and also for circuit design purposes. These include:

- Doherty type power amplifier
- mixer core
- micro-mixer transconductance stage
- basic current mirrors and differential pairs
- macro-model of a current-switching DAC.

## 7 Summary

This deliverable showed how the VoHB distortion contribution analysis was extended to operate in multi-device circuits and with multitude of device models. This was accomplished by the application interface AIF implemented for the APLAC simulator by AWR-Aplac and TKK-AALTO, through which we can now access all nonlinear devices and VCCS's of the circuit and enables to fit the polynomials that are used to calculate the distortion contributions as well as mixing gains. As AIF operates below the device model level, the implementation is independent of the used device models. The current implementation of VoHB is not limited by the size of the circuit. VoHB can be pretty easily used to pinpoint the devices that cause most of the distortion which can then be analysed in more detailed.

The main difficulties still lie in the fitting difficulties in multi-input sources. A frequency sampling method was implemented, that allows to modify the spectrums (especially the difference frequency beat tone at the output of a 2- or more input VCCS) used for polynomial characterisation. This has been shown to improve the numerical ease of the fitting, but care is still needed to maintain the operating conditions of the VCCS: the perturbation needs to be large enough to break the input-output correlation but small enough not to overdrive the circuit.

The implemented VoHB has been verified by two test circuits available by the project, and analysis of several other test circuit will be reported later in scientific publications.

## 8 References

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