# S-functions, the “S-parameters” for nonlinear devices

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**Abstract** – *This article describes the NMDG “S-functions” measurement-based behavioral model. When imported in simulators, S-functions, the “S-parameters” for nonlinear components, allow to accurately predict both harmonic and modulation behavior of cascaded components.*

## Introduction

For passive or active components used in their linear mode of operation, the S-parameters can be regarded as a measurement-based small-signal behavioral model of the device under test (DUT). Moreover, the small-signal network analysis is independent of the type of component and independent of the process technology.

Unfortunately, there is not yet such a uniform approach for dealing with nonlinear RF and microwave problems. However, one can deal with a subset of these phenomena in a uniform way using the NMDG S-functions. Derived from the describing functions introduced in the late 90s [1], the S-functions are a natural extension of S-parameters to model the nonlinear behavior of active components [2].

## The S-functions: mathematical theory and extraction method

In the late 90s [3-6], the describing functions, or “nonlinear scattering functions”, were introduced as a natural extension of S-parameters to model the nonlinear behavior of active components. Like with the S-parameters under linear conditions, the modeling approach is to relate the reflected waves (e.g. b1, b2) with the incident waves (a1,a2) under large-signal conditions. The NMDG S-functions are derived from this work.

To extract a small-signal behavioral model, the S-parameters can be measured at different DC bias points. One should notice that while they correctly describe the small-signal behavior of the component at each of these DC bias points, the S-parameters themselves become a nonlinear function of the DC operating points.

Under large-signal conditions, the above DC-bias-dependent S-parameters do not correctly describe the behavior of the component. To describe the nonlinear behavior of the component, some additional “bias” points are required: the fundamental input tones at each port of the DUT, i.e. the large-signal fundamental input tone a1(f0) which drives the DUT in its nonlinear mode of operation and the potentially-large tone a2(f0) reflected by the impedance presented at the DUT output port. Because the component is driven by this large-signal input tone, the reflected and transmitted waves will also contain harmonics.

Considering both the DC bias and the fundamental input tones a1(f0) and a2(f0), including their respective amplitude and their relative phase relationship, as part of the large-signal operating point (LSOP), one can already describe the nonlinear relationship between incident and reflected waves at both the input and output port of the device under mismatched conditions.

In addition, one can measure the “S-parameters” as a function of frequency by performing a forward and reverse measurement. Beyond the fundamental and harmonics at k.f0 resulting from the large-signal input tones and the small-signal input tone at frequency f, additional tones will show up at k.f0 ± f due to the inter-modulation products. A linear relationship does exist between the small-signal input tone at k.f0 ± f and the resulting output tones. This linear relationship also depends on the large-signal operating point and describes the behavior of the component due to perturbations on top of the large-signal input tones a1(f0) and a2(f0).

The combination of both the nonlinear and linear relationships is referred to as S-functions instead of S-parameters because of their dependency on the LSOP [2].

## Validity of S-functions

One should notice that the S-functions are valid under the following assumptions: each LSOP needs to remain constant while collecting data, the LSOP sweep plans are dense enough to allow correct interpolation and the perturbation signals on top of the input tones a1(f0) and a2(f0) are small enough in order not to violate the linear relationship assumption. It is important to be able to verify these assumptions before starting to use the models in a simulator tool.

## S-functions - an new application in ICE

In order to extract the model, a measurement system is needed to apply the different excitation signals to the DUT and to accurately measure the incident and reflected waves at the DUT ports level, under nonlinear conditions, including amplitude and phase relationship of the fundamental and harmonic spectral components.

True nonlinear characterization becomes possible with vector network analyzers from Rohde & Schwarz thanks to the ZVxPlus. Introduced in 2008, the ZVxPlus system [7], an NMDG extension kit running on top of selected Rohde & Schwarz ZVA and ZVT Vector Network Analyzers (referred to as ZVx), adds phase measurement capability to the power measurement of the harmonics. As a result the incident, reflected waves or voltages and currents waveforms at input and output of a DUT can be reconstructed in time domain to give complete insight in the harmonic behavior of that component interacting with the environment.

Among others, the add-on kit includes a software platform named ICE, running on the ZVx or on a separate PC via a standard interface bus (GPIB or LAN).

The Integrated Component Characterization Environment (ICE) is an evolutionary platform, making the latest expertise in device characterization, testing and modeling gradually available to the customer.

In contrast to instrumentation software, this software is device - centric. Indeed, the software brings together different stimuli, such as DC and RF sources or passive and active tuning techniques, and different receivers in a coherent way, complemented with the proper calibration techniques to provide almost in real time the calibrated voltage and current waveforms at the different ports of a device under test. At the same time, derived quantities such as input and output impedances, gain and power added efficiency (PAE) can be visualized.

Thanks to its flexibility and versatility, specific applications can also be developed in ICE that control the stimuli and capture the device behavior.

In June 2009, NMDG released the S-functions application in ICE. This application allows to collect measurement data for a sweep list of LSOP, i.e. sweeping of DC bias points and large signal input powers. The S-functions can be extracted for a given set of harmonics taking into account corresponding harmonic output impedances. The component does not have to be matched.

When applying the large-signal tone using an external source, the ZVxPlus can be reconfigured to extract the S-functions using the internal source of the ZVx to apply the small-signal input tone at the fundamental and at harmonics k.f0 either at the input or output of the DUT. One can also use the different tuning techniques to extract the S-functions in non-50 Ω conditions.

The model is then extracted in ICE using a simple push-the-button solution, while expert-level details are accessible if desired. A model verification tool is included; it does not require an external CAE tool and it enables one to validate the output predicted by the model based on an independent set of measurements.

## S-functions applicability

Like the S-parameters, S-functions can be cascaded. Imported in CAE tools, such as Agilent™ ADS or AWR® MWO, S-functions can then predict both harmonic and modulation behavior, under quasi-static assumption, from the component level up to the system level under non-50 Ω conditions in a uniform manner.

S-functions are also used within the ICE software platform itself and allow performing realistic simulation of large-signal measurements under various stimuli without the need for CAE tools.

In its actual implementation, the S-functions model deals with harmonically-related spectral components. However, thanks to its inherent mathematical formalism, S-functions can easily predict the behavior of a nonlinear component in presence of any small-signal spurious tone.

## Conclusion

By extracting measurement-based behavioral models via the S-functions, engineers can improve and speed up their design process by measuring and directly simulating RF systems under large-signal conditions. Manufacturers can also provide more complete system-level models of their RF devices.

**References**

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