

Proposed IEEE Online Course:

The Dynamics, Bifurcation, and Practical Stability Analysis/Design of Nonlinear High Frequency Circuits and Networks

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Version: 1.16.2021

Overall, this course seeks to teach the theoretical foundations for the stability analysis of high frequency circuits and networks, provide a detailed description of practical simulation tools allowing the prediction and suppression of instability phenomena (i.e., unwanted behavior that supplants the desired design behavior since the latter has become mathematically unstable and thus not physically observable), and present a survey concerning the harnessing of nonlinear effects for useful engineering purposes. The course will consist of several main components, as described in the following list, which will serve to determine the specific topics proposed below that will in turn become modules of instruction:

Component 1: Background & Motivation

Instability problems, often faced by designers of nonlinear microwave circuits and networks, are the cause of the qualitative differences found between the simulated and measured solution, the latter of which can contain incommensurate or subharmonic oscillation frequencies, or exhibit a continuous spectrum in some frequency bands (commonly known as chaos). Instability problems foster consequences ranging from increased production cycles and final costs to mission critical anomalies with exorbitant costs for investigation and resolution. Despite the strong relevance of stability problems (next only to the desired function of the subject design), there is, in general, a lack of background and rigor on this topic among high-frequency circuit and network designers that is especially prevalent in the nonlinear case. Too often, simple linear stability analysis approaches are misapplied in nonlinear contexts, leading to non-robust designs that can readily exhibit instabilities when parameters change.

Component 2: Nonlinear Dynamics Background

Nonlinear circuits and networks can exhibit one or more mathematical solutions, with different stability properties coexisting for the same element values. Only stable solutions are robust versus perturbations and will be physically observed. On the other hand, two or more stable solutions may coexist, which will give rise to changes in the solution observed depending on the initial conditions, and hysteresis phenomena when sweeping a circuit parameter, such as a bias voltage or input power. Background on nonlinear dynamics is necessary for the identification of the instability phenomena and the comprehension of the mechanisms for instability. To facilitate the attendee's development of a dynamical system perspective in general, which is now often missing in traditional engineering training, introductory material will be presented on steady-state solution types, stability concepts, and the dynamical system foundations of stability analysis for both the simple linear and much more complex nonlinear cases.

Component 3: Current Stability Analysis Practices and Their Improvement

In general, most designer's knowledge of stability analysis is limited to the Rollet factor and stability circles, which are only strictly valid for circuits and networks operating in small signal. Furthermore, these approaches are applicable only when the two-port described by scattering parameters is stable when unloaded. The course will show the limitations of these analysis

methods and will present rigorous techniques for the stability analysis of small- and large-signal solutions.

Harmonic-balance is usually the method of choice for the simulation of nonlinear microwave circuits due to the convenient frequency-domain description of distributed elements. This method provides the steady-state solution only, and the designer is often unaware of the fact that it is insensitive to the stability or instability of the solutions. The course will emphasize the need for complementary techniques for stability analysis, and also for the analysis of steady-state regimes containing self-generated oscillations. Nonlinear stability analysis techniques will be covered in depth, from theoretical foundations to practical implementations via in-house and commercial harmonic-balance simulators. The fundamental basis for these techniques is the introduction of small perturbations that leads to what is termed the characteristic system. Several primary nonlinear stability analysis approaches will be presented and compared, including a recent breakthrough approach that can provide a complete qualitative behavior diagram for a given circuit/network.

One of the distinguishing features of nonlinear systems is the phenomenon called bifurcation, in which the continuous variation of a circuit parameter leads to an abrupt qualitative stability change in the circuit's behavior. At this point, the nonlinear system evolves to a likewise qualitatively different type of solution. For instance, it may undergo a discontinuous jump in output power or an undesired oscillation may appear. In this course, the most common types of bifurcation will be presented and classified, enabling the designer to identify bifurcation phenomena in measurement and simulation. Simple mathematical conditions for bifurcation detection will be provided. These conditions can be easily applied by the user of commercial simulators to trace instability contours in a plane defined by two relevant design parameters. These contours can then be used to evaluate the impact of the instability on global circuit performance. They can also be used for efficient circuit stabilization through the inclusion of a stabilization element, such as a resistance, capacitance etc., which provides an additional analysis parameter.

We will present practical examples of instability in nonlinear circuits and networks such as power amplifiers, frequency multipliers/dividers and voltage-controlled oscillators. In each case, we will show the stability analysis procedure, the impact of instability on circuit/network performance (for instance, in the measured spectrum), and techniques for stabilization.

Component 4: Exploiting Nonlinear Dynamics Effects

In most instances, designers want to minimize behavioral effects due to circuit/network nonlinearities. But on the flip side, it turns out that many nonlinear effects can be exploited for engineering application. Perhaps the most prominent of these effects is the deterministic, but noise-like behavior called chaos, which has been used for random sequence generation, communications, radar, signal processing, encryption, and many other applications. The course will end with an enlightening survey of nonlinear engineering that is being vigorously undertaken on an international scale.

Proposed Topics/Outline (consisting of one or more modules per topic):

1 — Introduction to Stability Analysis

- 1.1 — *What is stability and why is it important?*
- 1.2 — *Brief survey of current stability analysis practices*
- 1.3 — *Motivation for dynamics-based, nonlinear stability analysis*

2 — Classical Dynamical Systems, Bifurcation, & Stability Overview

3 — Simulation Analysis of High Frequency Circuits & Networks

- 3.1 — *Time domain versus frequency domain approaches*
- 3.2 — *Fundamentals of harmonic balance method*
- 3.3 — *Auxiliary-generator technique*

4 — Stability Analysis of DC Solutions

5 — Small-Signal Stability Analysis

- 5.1 — *Limitations of current stability analysis techniques*
- 5.2 — *Methods based on Nyquist plots: Perturbed harmonic-balance system and normalized determinant function*
- 5.3 — *Pole-zero identification*

6 — Large-Signal Stability Analysis

7 — Bifurcation Phenomena

- 7.1 — *Bifurcation conditions and implications on circuit behavior*
- 7.2 — *Detection and parametric mapping using auxiliary generators and recent improved approaches*
- 7.3 — *Circuit examples: power amplifiers, voltage-controlled oscillators, analog frequency dividers and multipliers*

8 — Stability Analysis/Design of Power Amplifiers

- 8.1 — *Local and global analysis*
- 8.1 — *Stabilization design techniques*
- 8.2 — *Stability criteria under mismatch effects*

9 — Stability Analysis in Presence of Modulated Signals

10 — Exploitation of Nonlinear Dynamics

11 — Summary & Conclusion

Modules will be in the form of presentations featuring fundamental dynamics-based principles, detailed technical analysis and simulation methods (latter including their implementation in commercial EDA platforms), practical analysis/design application examples, and videos of simulation exercises and hardware demonstrations.