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# Frequency-Domain Stability Analysis of Non-Linear Circuits driven by Random Modulated signals.

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**Abstract** — A frequency-domain stability analysis of non-linear circuits driven by a microwave Random-Modulated (RM) signal is presented. This stability analysis generalizes the already proposed method for CW generators to random modulated signals. The method is applied to perform the stability analysis of a designed and fabricated 20W/S-Band Quasi-MMIC GaN asymmetric Doherty Power Amplifier (DPA). The amplifier operates in the 3.2-3.6GHz bandwidth. It is driven by a generator modulated by a 16 QAM signal at 10MS/s. The simulated dynamic and stability results are all extracted from a frequency-domain simulation.

**Keywords** — circuit simulation; demodulation; frequency-domain analysis; harmonic balance; linearity; modulation; non-linear circuits; pseudo-random generation, local stability analysis

## I. INTRODUCTION

In the current and future telecommunication standards (5G and beyond), the carrier frequency increases towards millimeter bands, and the modulation schemes become more and more complex. Therefore, it is mandatory for the microwave designers to have an accurate and reliable software design tool that allows, in the same Harmonic Balance (HB) simulation-frame at circuit-level, the simulation of microwave devices and subsystems with Continuous Wave (CW) or with Random-Modulated (RM) RF sources. A fundamental step in the design process of an amplifier at the circuit level consists in verifying the linear and non-linear local stability of the amplifier driven by CW and by RM signals really used in actual communication front-ends. This paper presents the simulation in the frequency domain of the local stability of non-linear circuits driven by a microwave Random-Modulated (RM) generator.

In order to perform the simulation with harmonic balance techniques, the RM microwave large signals are generated by periodizing the random bit sequences allowing almost periodic HB simulation.

The stability analysis method is applied to the simulation of an asymmetric packaged Quasi-MMIC SI-DPA. We recall first the stability analysis for a CW driving generator [1] and then we detail the proposed extension to RM signals. We applied it to a 16-QAM Random-Modulated (RM) generator. The analysis is performed in association with the STAN<sup>®</sup> software [2].

## II. SIMULATION OF NON-LINEAR CW LOCAL STABILITY

The large signal state variables in the circuit are periodic, with fundamental angular frequency  $j\omega_0$  corresponding to  $f_0$ . The circuit appears to a small signal perturbation, as a Linear Periodically Time Varying (LPTV) circuit. The conversion-

matrix describing the mixing between a small-signal with a fundamental frequency  $j\Omega$  and a large-signal with a fundamental frequency  $j\omega_0$  in a non-linearity is a well-known 1D Matrix. A small signal probing (perturbation) current source with an angular frequency  $j\Omega$  is connected between a node  $k$  of the circuit and the ground as shown in Fig. 1. Note that  $\Omega$  excludes all the large signal frequency components at  $n\omega_0$  in order to avoid any synchronous operation.

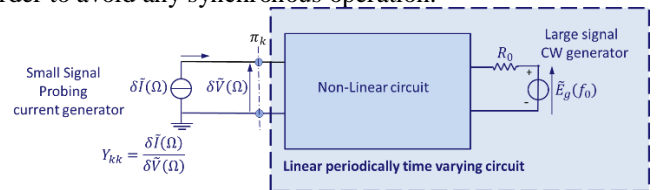


Fig. 1. Principle of Non-linear CW Local Stability Analysis

First, via an identification procedure [2] performed with the STAN<sup>®</sup> software, the driving point admittance  $Y_{kk}(j\Omega)$ , in the  $j\omega$  real frequency-domain, seen by the small-signal current generator is fitted.

Secondly,  $Y_{kk}(p)$  is then identified in the complex frequency domain ( $p = \sigma + j\omega$ ) with a vector fitting algorithm [3].

$$Y_{kk}(j\Omega) = \frac{\delta I_k(j\Omega)}{\delta V_k(j\Omega)} = \frac{Det[M_c(j\Omega)]}{C_{kk}(j\Omega)} \Rightarrow Y_{kk}(p) = \frac{\delta I(p)}{\delta V(p)} = \frac{Det[M_c(p)]}{C_{kk}(p)} \quad (1)$$

$C_{kk}(p)$  is the cofactor associated to the node  $k$ .

Equation (1) verifies a well-known result: the driving point admittances  $Y_{kk}(p)$  at all nodes share the same numerator which is the determinant of the whole circuit:  $Det[M_c(p)]$ .

The STAN<sup>®</sup> software determines then the zeroes of the driving point admittance  $Y_{kk}(p)$ . These zeroes are described as:

$$p_{zr} = \sigma_{zr} + j\omega_{zr} \quad (2)$$

$p_{zr}$  are also named Floquet exponents [4]. They correspond to the zeroes of the determinant  $Det[M_c(p)]$  of the whole LPTV circuit.

Each  $p_{zr}$  Floquet exponent belongs to a class of equivalent Floquet exponents defined to within the following constant  $p_{zr} + j.n.\omega_0$  where  $n$  is an integer [5], [6]

But, all the Floquet exponents of a same class share the same  $\sigma_{zr}$  real part. The sign of this real part ( $\sigma_{zr}$ ) of the Floquet exponents decides of the stability of the circuit:

- If the real part of the zeroes is negative ( $\sigma_{zr} < 0$ ), the circuit is locally stable,
- If there is a positive real part ( $\sigma_{zr} \geq 0$ ), the circuit is then locally unstable.

The theoretical frequency-range of the perturbation to be swept for rigorous local stability analysis of non-linear circuit

driven by a one-tone CW large signal in the pink shaded frequency band is shown in Fig. 2.

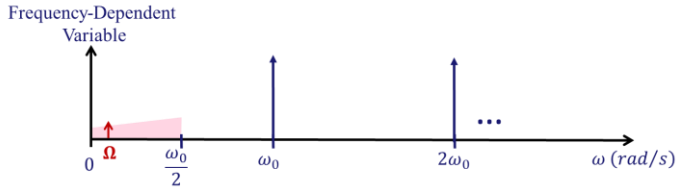


Fig. 2. Frequency Range for local stability analysis of the DPA circuit with STAN<sup>®</sup> software.

Due to the frequency conversion inherent to the LPTV circuit which generates side-bands around all the large signal  $k\omega_0$  frequencies, the  $\Omega$  pulsation range of the small-signal perturbation generator for local stability analysis can be restricted to the following range:

$$0 < \Omega < \frac{\omega_0}{2} \quad (5)$$

We practically choose a wider frequency range than the theoretical minimum necessary shown in Fig. 2. The chosen larger bandwidth will allow a better fitting of the complex admittance  $Y_{kk}(j\Omega)$  and an accurate identification of  $Y_{kk}(p)$ . The zeroes of the admittance presented to the perturbing generator are determined in function of the input power of the large signal generator by sweeping it, and calculating the Floquet exponents at each power-step.

The DPA is simulated with the configuration given in Fig. 3. Fig.3 represents the schematic for the CW Local stability simulation of the DPA. This circuit is probed by a small-signal (perturbing) current source  $\delta I(\Omega)$  (“I\_1tone SRC3” Source in the schematic of Fig. 3) connected to the gate node of the main stage.

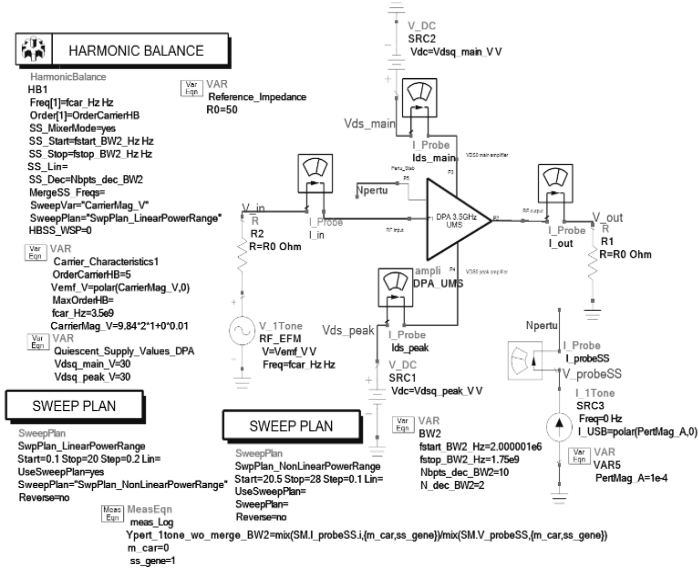


Fig. 3. Schematic of the HB 1 tone CW simulation for stability analysis.

The CW simulation for stability analysis, performed on a X64-based desktop PC with Intel<sup>®</sup> Core<sup>™</sup> i7-10810UCPU@1.1GHz, 1.61 GHz, 6 Core(s) and 16GB of RAM, leads to runtime equal to 377.08 seconds to deal with a sweep of 177 levels of the EMF voltage source and with 30

frequencies of the small signal perturbation current source.

The local stability is carried-out for several average input levels. Fig. 4 presents the Floquet exponents  $p_{zr}$  obtained from the STAN<sup>®</sup> software for the 3 chosen power levels.

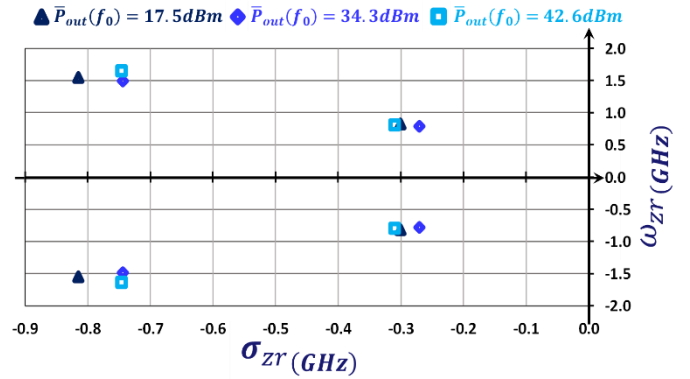


Fig. 4. Floquet exponents  $p_{zr}$  obtained from the STAN<sup>®</sup> software for the 3 chosen power levels in CW large signal regime.

It can be easily seen in Fig. 4 that the real parts of the calculated zeroes are negative ( $\sigma_{zr} < 0$ ). It can be deduced then that the DPA is locally stable for the 3 input levels. The conclusion is exactly the same for all the swept carrier magnitudes of the CW Local stability simulation of the DPA

### III. NON-LINEAR LOCAL STABILITY OF THE DPA DRIVEN BY PSEUDO-RANDOM MODULATED CARRIER GENERATOR

The non-linear circuit is now driven by a pseudo-random modulated generator. As presented and detailed in [7], the generator is considered as a Pseudo-Random Modulated electromotive force, and the large-signal simulation can be now performed by Almost-Periodic Harmonic Balance techniques (RM-HB). The large-signal frequency grid is determined using two fundamental frequencies: the first one is associated to the carrier frequency ( $f_{car}$ ) and the second one is related to the random modulation sequence ( $f_{modframe}$ ). The value of  $f_{modframe}$  is calculated as the inverse of the modulation frame time length [7].

For an M-QAM modulation, with M complex levels, the frame length corresponds to an integer number of the M, in order to obtain and to ensure an equiprobability of the generated symbols within the frame sequence.

The expression of large signal voltages in a non-linear circuit driven by a pseudo-random modulated generator is defined in (36).

$$v_{modN,K'}(t) = \Re\left\{\left[\sum_{k=1}^{K'}(A_{k,0}e^{j\varphi_{k,0}})e^{j2\pi k f_{modframe}t}\right]\right\} + \Re\left\{\sum_{n=1}^N\left[\sum_{k=-K'}^{K'}(A_{k,n}e^{j\varphi_{k,n}})e^{j2\pi k f_{modframe}t}\right]e^{j2\pi n f_{car}t}\right\} \quad (36)$$

with  $n f_{car} + k f_{modframe} \geq 0$

The frequency spectrum of  $v_{modN,K'}(t)$  is shown in Fig. 5. In this figure, the variables are the following ones:

- $\omega_{car}$ : the fundamental carrier pulsation,
- $N \cdot \omega_{car}$  the maximum order of carrier harmonics retained for the analysis of the non-linear circuit,
- $\omega_{modframe}$ : the fundamental pulsation modulation

( $\omega_{modframe} = \frac{2\pi}{T_{modframe}}$ ), with  $T_{modframe}$ , the period of the modulating random bit sequence,

- $K \cdot \omega_{modframe} = 2\pi \cdot BW_{bb}$ : the truncated modulation bandwidth of the modulated RF electromotive force generator,
- $K' \cdot \omega_{modframe} = 2\pi \cdot BW'_{bb}$ : the truncated modulation bandwidth retained for the analysis of the non-linear circuit.

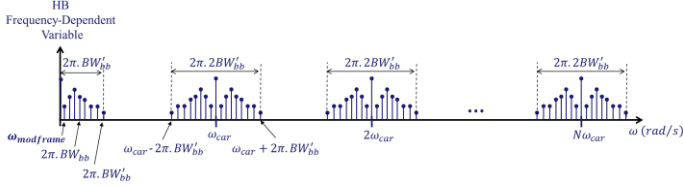


Fig. 5. Frequency grid of  $v_{mod,N,K'}(t)$  spectrum

For the analysis of the local stability of a non-linear circuit driven by two large signals, the frequency domain procedure previously described for a large signal CW generator case has been extended to an almost periodic driving generator.

From the mixing theory, it may be theoretically shown that in a non-linear circuit driven by two large signals at  $j\omega_{car}$  and  $j\omega_{modframe}$ , and a small signal (probing) at  $j\Omega$ , the large signal state variables in the circuit become 2D (almost) periodic. The conversion-matrix describing the mixing between the large-signal and small-signal in a non-linearity becomes a 2D conversion-matrix, with two large-signal fundamental frequencies  $j\omega_{car}$  and  $j\omega_{modframe}$ , as shown in Fig. 6.

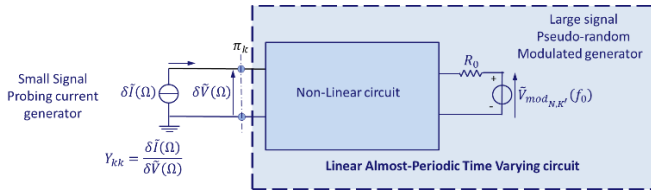


Fig. 6. Principle of Non-linear LAPTIV Local Stability Analysis

The local stability of the DPA driven by pseudo-random modulated carrier generator is then determined in the frequency-domain as follows:

- A probing small signal current generator, at frequency  $j\Omega$ , with  $\Omega \neq q \cdot \omega_{car} \pm p \cdot \omega_{modframe}$  is connected between a node  $k$  of the circuit and the ground.
- The non-linear circuit, driven by the two large signal fundamental frequencies:  $j\omega_{car}$  (carrier) and  $j\omega_{modframe}$  (length of the modulating random bit sequence), appears then as a Linear Almost Periodically Time Varying (LAPTIV) Circuit to the (small signal) probing current generator of Fig. 6. Note that the circuit can be simulated in small-signal-large-signal mode or in almost periodic HB three-tone mode with two large-signal (Local Oscillators) generators at  $j\omega_{car}$  and  $j\omega_{modframe}$ , and one small-signal generator at  $j\Omega$ . In both cases, the whole circuit works in the so-called mixer mode.
- The (small signal) driving port admittance:  $Y_{kk}(j\Omega)$  seen

by the probing current generator is first simulated.

As for the previous CW case, via an identification procedure [2] performed with the STAN<sup>®</sup> software, the admittance  $Y_{kk}(j\Omega)$  seen by the small-signal current generator in the real frequency domain  $j\omega$ , is identified in the complex frequency domain:  $Y_{kk}(p)$  as previously defined in [1].

The driving point admittances  $Y_{kk}(p)$  share at all nodes the same numerator which is the determinant of the whole circuit:  $Det[M_c(p)]$ .

The numerator  $Det[M_c(p)]$ , captures all the Floquet exponents of the whole circuit  $p_{zr} = \sigma_{zr} + j\Omega_{zr}$ . The software STAN<sup>®</sup> determines all the Floquet exponents ( $p_{zr} = \sigma_{zr} + j\Omega_{zr}$ ) of the LAPTIV circuit:

- If the real part of all  $\sigma_{zr}$  zeros are negative, the circuit is locally stable.
- If there is a positive real part of any  $\sigma_{zr}$  zero, the circuit is locally unstable.

In order to study the local stability in the  $[0; \frac{\omega_{car} + 2\pi \cdot BW'_{bb}}{2}]$  frequency range, and since the circuit appears as almost periodic with respect to the perturbation frequency (mixer mode), the small signal perturbation generator should be theoretically swept in the following frequency-range  $0 < \Omega < \frac{\omega_{car} + 2\pi \cdot BW'_{bb}}{2}$ .

The chosen bandwidth, identical as the one use for the CW stability  $[0 < \Omega < \frac{\omega_{car}}{2}]$  frequency range, will also allow an appropriate fitting of the complex admittance  $Y_{kk}(j\Omega)$  and an accurate identification of  $Y_{kk}(p)$ .

Please recall that the numerical values of the small-signal frequencies must exclude the large signal frequencies present in the circuit.

In Fig. 7, the following needed frequencies for the stability analysis are shown:

- $\omega_{car}$ : the fundamental carrier pulsation
- $\omega_{modframe}$ : the fundamental modulation pulsation.
- $\Omega$ : swept pulsation of the small-signal perturbation generator for local stability analysis  $[0; \frac{\omega_{car} + 2\pi \cdot BW'_{bb}}{2}]$ .

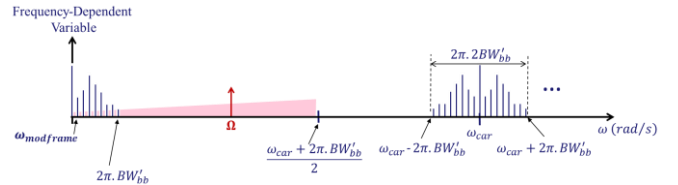


Fig. 7. Principle of non-linear LAPTIV local stability Analysis (Red arrow: chosen perturbation sweep  $[0 < \Omega < \omega_{car} + 2\pi \cdot BW'_{bb}/2]$ , Blue arrows: large signal spectrum).

First, a spectral balance analysis of the large signal state variables of the circuit is performed. The circuit seen by the perturbation becomes then a Linear Time Varying (LTV) circuit.

As for the CW case, after identification, the zeroes of the driving point admittance  $Y_{kk}(p)$  presented to the small-signal current generator are calculated in function of the input power

by sweeping the average input power of the large signal pseudo-random modulated carrier, and calculating the Floquet exponents at each power-step.

As for the CW case, after identification, the zeroes of the driving point admittance  $Y_{kk}(p)$ , presented to the small-signal current generator, are calculated in function of the input power by sweeping the average input power of the large signal pseudo-random modulated carrier, and calculating the Floquet exponents at each power-step.

This proposed frequency-domain analysis of local stability for non-linear circuits driven by pseudo-random modulated signals extends the method proposed in [1] for CW driven non-linear circuits.

The designed DPA is then simulated with the similar configuration given in Table III. Fig. 8 shows the schematic for the PRM-HB local stability simulation of the designed and fabricated DPA.

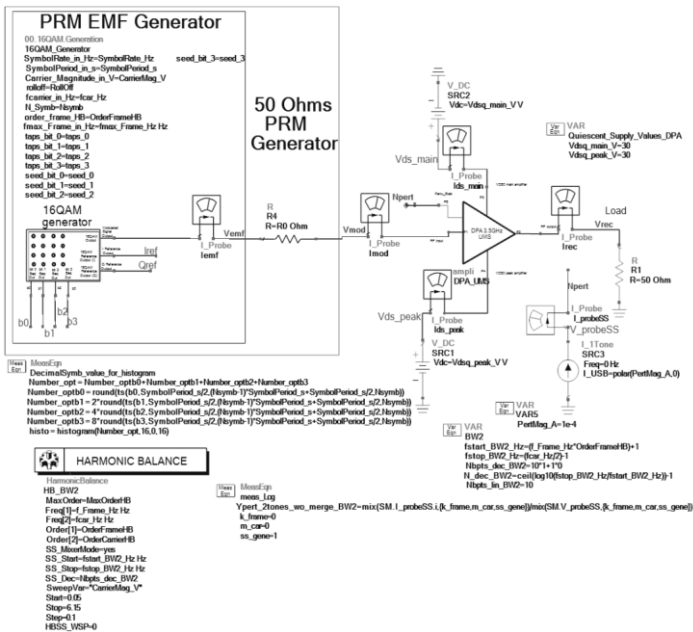


Fig. 8. Schematic of the PRM-HB simulation for local stability analysis.

The PRM-HB simulation for stability analysis, performed on the same X64-based desktop PC leads to runtime equal to 62601.7 seconds to deal with a sweep of 61 levels of the EMF voltage source and with 30 frequencies of the small signal perturbation current source.

Fig. 9 presents the Floquet exponents  $p_{zr}$  obtained from the STAN<sup>®</sup> software for the 3 chosen power levels. It can be easily seen in Fig. 12 that the real parts of the calculated zeroes are negative ( $\sigma_{zr} < 0$ ). It can be deduced then that the DPA is locally stable for the 3 input levels.

The conclusion is exactly the same for all the swept carrier magnitudes of the PRM-HB Local stability simulation of the DPA.

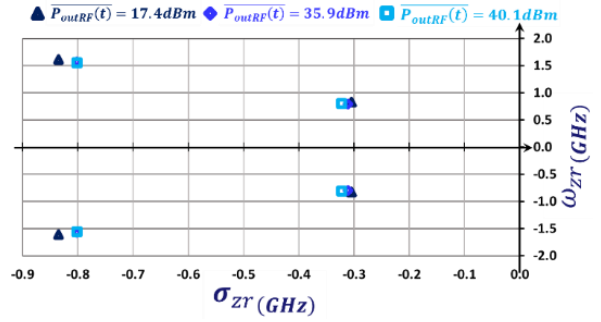


Fig. 9. Floquet exponents  $p_{zr}$  obtained from the STAN<sup>®</sup> software for the 3 chosen power levels.

#### IV. CONCLUSION

This paper presents the analysis of the local stability of a non-linear circuit driven by a microwave pseudo-random modulated generator. The simulation is performed in the frequency-domain, using harmonic balance techniques. This process is a generalization of the method previously proposed by [1] for continuous wave (CW) generators to randomly modulated signals. It can be applied to any RM signal and, for example, to OFDM signals. Indeed, it is mandatory that designers have an accurate and reliable software design tool, at the circuit level, allowing in the same HB simulation-frame, the simulation of microwave devices or subsystems with continuous wave (CW) or with random-modulated (RM) microwave sources really used in actual communication front-ends.

#### ACKNOWLEDGMENT

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