A Figure of Merit for the Evaluation of Long Term Memory Effects in RF Power Amplifiers

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Abstract—This paper proposes a long term memory effect figure of merit, FOM, that can be easily measured in a microwave laboratory and has a simple interpretation in the power amplifier, PA, linearization field. For that, a brief explanation of the long term memory effects' origins in a RF PA is first presented, and then, the concept of the optimum memoryless PA linearizer is introduced. This is used to define a FOM capable of classifying PAs from a slow dynamics perspective.

Index Terms—Power amplifiers, Nonlinear systems, Long term memory.

I. BACKGROUND

Memory effects, MEs, have been receiving a great deal of attention from microwave power amplifier, PA, design engineers as they are known to impair most common (memoryless) PA linearization schemes.

Short term MEs involve time constants of the order of the period of the microwave excitation and are caused by both the reactive components of the active device and the input and output matching networks. Since these MEs are much shorter than the information time scale, a PA presenting only short term MEs will behave as static for the information signal, reason why it is usually treated as being memoryless.

On the contrary, long term MEs are low frequency phenomena (from dc to a few kHz or MHz) involving time constants that are comparable to the information time scale. Thus, they can press dynamic effects onto the envelope being processed. Unless very high Q components are used in the matching networks, these long term MEs can only arise from some form of dynamic nonlinearity. They are usually attributed to the active device’s dynamic thermal effects (i.e. involving some sort of thermal inertia), the active device’s charge carrier traps or to the biasing networks. From a behavioral viewpoint, they show up as hysteresis in the AM/AM and AM/PM plots, different two-tone intermodulation, IMD, characteristics for varying tone spacing, IMD asymmetry or even transient step response of an ON-OFF CW test. Long term MEs are so much more important than their short term counterparts that anytime MEs are mentioned it is the long term ones that are being referred, unless otherwise is expressly stated.

It is in the PA linearization field that these MEs (the long term MEs) have been playing the leading role, as they are turning an already difficult task into an almost impossible mission [1,2]. In fact, since traditional PA linearizers are designed as memoryless devices, they simply breakdown in presence of some sort of dynamic IMD behavior. This is so important that microwave PA industry has been asking for some form of MEs metric, capable of evaluating the PA linearizability under static, or memoryless, conditions.

A first attempt to respond to this solicitation of microwave industry was proposed by Ku, McKinley and Kenney in [3]. In this work, they assume that the best memoryless linearizer of the PA under evaluation is the one that exactly compensates the measured AM/AM-AM/PM characteristics. Then, they defined a metric of memoryless PA linearization as the normalized ratio (to the AM/AM-AM/PM) of the deviations of the actual PA two-tone IMD from this AM/AM-AM/PM baseline. Although useful, this metric has been difficult to apply in the industrial environment because of two main reasons.

First, it was conceived and defined under the development of a PA parallel Wiener behavioral model [3]. So, it gives the impression that it can only be applied after the model is extracted. Second, and most important, it relies on the assumption that the best memoryless linearizer is the one obtained from the AM/AM-AM/PM characteristics. Unfortunately, if we recognize that these characteristics are the extrapolated two-tone IMD when the tone separation tends to zero, and we remember that most of the PA memory effects come from an inductive output bias circuit, we immediately conclude that such a memoryless linearizer is not the best we can do to linearize our PA even under static conditions. In fact, many microwave PA engineers have already noticed that detuning this AM/AM-AM/PM linearizer easily produces much better linearization results, although keeping its memoryless condition. Hence, the problem of finding a useful metric of PA’s MEs that can be used as a measure of the PA linearizability under memoryless conditions still constitutes an open problem.

II. LONG TERM MEMORY EFFECTS

In order to better understand the long term memory mechanisms in PAs, let us consider a simple PA based on an active device, for instance, the FET PA shown in Fig. 1. We can model this circuit using a Volterra series description, and then relate the IMD behaviour to its circuit components.
Since this type of Volterra decomposition is well known from previous publications [4,5], we will only present here the transfer function for the third order IMD, corresponding to the spectral regrowth at $2\omega_2-\omega_1$:

$$H_3(\omega_2, \omega_3, -\omega_1) = \frac{G_m}{3} \left( \frac{2H_2(\omega_2, -\omega_1)Z_L(\omega_2 - \omega_1) + H_2(\omega_2, \omega_3)Z_L(\omega_2 + \omega_3)}{1 + G_mZ_L(2\omega_2 - \omega_1)} \right)$$

(1)

where:

$$H_2(\omega_1, \omega_2) = \frac{G_m}{2} \left[ \frac{H_1(\omega_1)Z_L(\omega_1) + H_1(\omega_2)Z_L(\omega_2)}{1 + G_mZ_L(\omega_1 + \omega_2)} \right]$$

(2)

and

$$H_1(\omega) = \frac{G_m}{1 + G_mZ_L(\omega)}$$

(3)

From this simple model, it is easily seen that the third order IMD output will comprise three different components: one is a direct term arising from $G_m$ that does not depend on $\omega_2-\omega_1$; a second order term arising from the $(\omega_1+\omega_3)$ band, which also does not depend on $\omega_2-\omega_1$; and finally, a term that can be interpreted as an up-conversion of the base-band components back to the fundamental frequencies. This can be represented by the model shown in Fig. 2 [6].

![Fig. 2. Model for the PA’s long term memory mechanisms.](image)

Now, assuming this PA model is excited by a frequency-domain input signal $x(t) \rightarrow X(\omega)$, the output IMD at $2\omega_2-\omega_1$ can be given by:

$$Y(2\omega_2 - \omega_1) = H_{31}(2\omega_2 - \omega_1)X(\omega_1)X(\omega_2)X(\omega_1)X(\omega_2)X(\omega_1) + H_{22}(2\omega_2)X(\omega_2)X(\omega_2) + H_{BB}(2\omega_2 - \omega_1)X(\omega_2)X(\omega_2)X(\omega_1)$$

(4)

If we consider that $H_{22}()$ and $H_{31}()$ are constant with $\Delta\omega=\omega_2-\omega_1$, then the output IMD variation will only depend on $H_{BB}(\Delta\omega)$, and thus this $H_{BB}(\Delta\omega)$ will be the exclusive responsible for the PA long term memory effects.

This assumption is reasonable, since as $\Delta\omega$ varies from DC up to a few MHz, the base band frequency will vary for some decades, while the second harmonic and the fundamental will only vary a small percentage of the center frequency.

Important information that can be gathered from both models is as follows. First, if any of the $H_{31}$ or $H_{22}$ terms is significantly higher than the one involving $H_{BB}$, we can be misled by the fact that variation in IMD with $\Delta\omega$ may not be evident, although the PA still presents memory effects that will impair the performance of a memoryless linearizer. Second, the IMD asymmetry (different upper and lower IMD components at $2\omega_2-\omega_1$ and $2\omega_2+\omega_1$, respectively) only appears in case both output impedances at $\omega_2-\omega_1$ and $\omega_2+\omega_1$ are complex. In this simple model this implies that either the direct path or the second harmonic path contributes with a certain amount of imaginary values [4]. This has a strong impact in the knowledge of these problems, since it states that we can have long term memory effects, even without IMD asymmetry.

Since it is only the memory that we would like to capture, if we null the constant part, and thus the one that does not change with frequency spacing, we will obtain the remaining term that changes with tone spacing. In expression (4) the constant part corresponds to $H_{31}$ and $H_{22}$. So our goal is to capture the part of $H_{BB}(\omega_2-\omega_1)$.

With this knowledge in mind, let us now define a new figure of merit for long term memory effects.

III. FOM FOR PA LONG TERM MEMORY EFFECTS

The performed analysis showed that, although the two-tone IMD must, in general, be modeled through a three-dimensional nonlinear transfer function, it can be also represented via a one-dimensional frequency-domain transfer function of the tone-spacing, $\Omega=\Delta\omega$. In fact, that is the same assumption behind the widely adopted nonlinear-integral-model [7], or the nonlinear-impulse-response-model [8]. Moreover, it should be said that a swept $\Delta\omega$ two-tone test of a PA around the operating central frequency, is implicitly assuming this one-dimensional nature.

So, expression (4) can be viewed as $Y_{BB}(\Delta\omega) = Y(\omega_2+\Delta\omega)$, which is the measured (or, possibly, calculated) PA two-tone response used for defining the new ME metric.

The next step consists in defining the best memoryless linearizer of the PA. For that, we assume the general block diagram depicted in Fig. 3, in which the linearizer is used to generate an auxiliary IMD that will compensate the one produced by the stand-alone PA.

![Fig. 3. General PA linearization arrangement.](image)
conceptual addition (in fact, subtraction) of the IMD produced by the PA and its linearizer.

Under this conceptual linearization scheme, we now define the optimum memoryless linearizer for a given PA as the static (or constant with frequency $\Omega$) auxiliary device of Fig. 3, $C$, that minimizes the distortion power in the considered operation bandwidth, $W$:

$$C : \int_{-W}^{+W} [C - Y_{BM3}(\Omega)]^2 d\Omega$$

is minimum \hspace{1cm} (5)

This expression states that our memoryless linearizer is a mean square error constant estimator, which can be determined by:

$$\frac{d}{dc} \int_{-W}^{+W} [C - Y_{BM3}(\Omega)]^2 d\Omega = 0 \Rightarrow C = \frac{1}{2W} \int_{-W}^{+W} Y_{BM3}(\Omega) d\Omega$$ \hspace{1cm} (6)

Therefore, the optimum linearizer is nothing more than the vectorial mean of the $Y_{BM3}(\Omega)$ response within the bandwidth of interest. It can be easily estimated in a microwave laboratory measuring $Y_{BM3}(\Omega)$ in amplitude and phase over the desired bandwidth.

To get a deep insight of what such an optimum memoryless linearizer is, we now turn to the time-domain. For that, we perform the inverse Fourier transform of $Y_{BM3}(\Omega)$ of (6) to obtain:

$$C = \frac{1}{2W} \left[ \int_{0}^{\infty} \int_{-W}^{+W} y_{BM3}(\tau)e^{-j\Omega \tau} d\Omega d\tau \right]$$

$$= \int_{0}^{\infty} y_{BM3}(\tau) \text{sinc}(W\tau) d\tau$$ \hspace{1cm} (7)

where $\text{sinc}(x) = \sin(x)/x$.

Then, we will study two limit situations of the tested bandwidth.

First, we will impose no restriction in the bandwidth, letting $W \rightarrow \infty$. In this case, $\text{sinc}(W\tau)$ becomes a very narrow function (a Dirac delta function) around zero and (7) gives $C = Y_{BM3}(0)$. This means that the optimum memoryless linearizer is such that it cancels out the PA instantaneous (or memoryless) IMD, exactly what we were expecting it to do.

Now, we consider the opposite situation in which $W \rightarrow 0$. This is the case where $C$ is made equal to $Y_{BM3}(0)$, the AM/AM-AM/PM characteristics. $\text{sinc}(W\tau)$ is now a very wide and flat function, and $C$ becomes:

$$C = \int_{0}^{\infty} y_{BM3}(\tau) d\tau$$ \hspace{1cm} (8)

the average of the $y_{BM3}(\tau)$ impulse response tail. So, the AM/AM-AM/PM linearizer can only be optimum whenever the amplifier is processing a signal whose envelope bandwidth is much smaller than the PA swept tone spacing characteristics, or the temporal IMD dynamics is much slower that the PA memory span.

Now that we have defined the optimum memoryless linearizer, we are in position to define the aimed FOM of PA linearizability under static conditions. Intuitively, this should measure the ratio of integrated IMD power in the desired bandwidth, after memoryless linearization, to the integrated power of total unlinearized IMD in the same bandwidth of interest:

$$L_M = \frac{\int_{-W}^{+W} [Y_{BM3}(\Omega)]^2 d\Omega}{\int_{-W}^{+W} [Y_{BM3}(\Omega)]^2 d\Omega}$$ \hspace{1cm} (9)

Although defined and justified in the frequency-domain, such a FOM can reveal an even more interesting significance when seen in the time-domain. For that, we consider again the case where we are interested in the whole PA IMD bandwidth characteristics, i.e., $W \rightarrow \infty$. Since, in that case, $C = Y_{BM3}(0)$, the Parceval's theorem tells us that our FOM is, actually, a metric of the power only contained in the PA dynamic IMD, normalized to the total IMD power. Thus, the $L_M$ of (9) is, indeed, a metric of PA long term memory effects.

IV. SIMULATION OF THE FOM FOR LONG TERM MEMORY EFFECTS

In this section two nonlinear PAs were simulated, one is memoryless and the other presents some form of memory.

The simulated PAs were based on a FET device operating near the 1dB compression point. The biasing networks are resistive in the first case and inductive in the second one. The test was performed with a two-tone signal centered at 1.8GHz and tone spacing varying from 1kHz to 2MHz.

![Simulation of the memoryless PA before linearization and after linearization](image)

Fig. 4. Simulation of the memoryless PA before linearization and after linearization.

Fig. 4 presents the value of IMR before and after linearization using the optimum linearizer for the PA of static bias network. The value of the linearized IMD is constant over the frequency and its residual value is determined by the numerical error of the simulator. The PA FOM is 46dB.

Fig. 5 presents the case of a PA presenting memory. In this case the value of the IMR before and after the linearization varies with frequency. Moreover, the minimum value of the IMR after linearization is 13dB, considerably smaller than in the case of the memoryless one. The FOM in this case has thus a much lower value of 21.9dB.
optimum memoryless linearizer the distortion energy could be reduced by 22.1 dB.

Fig. 7 presents the IMR results for the second amplifier. As can be seen, the linearizability of this amplifier is much smaller than the previous one. This is naturally expressed by the lower value of the FOM that is only 8.2 dB.

VI. CONCLUSIONS

This paper presented a metric for the evaluation of the memoryless linearizability of a PA when affected by long term memory effects. This metric was given as an intuitive and easily measurable figure of merit (FOM), defined as the IMD power obtained after optimum static linearization, normalized to the total unlinearized IMD power. Since, seen from the time-domain, this FOM is also a metric of the normalized PA memory, it can be extremely useful to classify PAs according to their long term memory effects and memoryless linearizability.

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