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Robust Linearization of RF Amplifiers Using NonLinear Internal Model Control Method

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Abstract—In the present paper, the nonlinear Internal Model Control (IMC) method is introduced and applied to linearize high frequency Power Amplifiers (PAs). The IMC is based on the description of a process model and of a controller. It is shown that baseband frequency descriptions are suitable for the model and the controller. Their description parameters are derived from input and output modulation signals processed in Cartesian form. Simulation results are given to illustrate the design procedure and to demonstrate the performances of the IMC linearizer.

I. INTRODUCTION

Traditionally, techniques used for amplifiers linearization are based on predistortion and feedback techniques [1][2][3]. The predistortion technique involves the creation of an inverse characteristic complementary to the amplifier nonlinearity [4][5]. Performances can be improved by adding a feedback control to deal with external perturbations, parameter variations or operating frequency modifications. Design of conventional feedback circuit requires considering carefully performances in term of gain-bandwidth product and stability [6][7]. The nonlinear IMC is an alternative solution using a model of the nonlinear system to be controlled [8]. If the model is a perfect representation of the non linear system, the controller can be design without concern for system stability. Furthermore, the control method of the IMC is very simple and comprehensive, leading to an easy tuning of the controller parameters.

For radio communications applications, the model and the controller are difficult to design because of the high operating frequency used and time delay introduced [9][10]. A solution consists in using baseband signals to describe the behavior of system parts. For feedback implementation, an error signal can be given by the comparison of the input and output envelope signal [11][12]. More advanced techniques used polar or Cartesian signal formats to take into account the phase distortion [1][13]. In this paper, we proposed to design an IMC structure using Cartesian signal. The model and the controller are then described by mathematical expressions derived from measurements of the downconverted output signals and of the input modulating signal. Then, the technique results in the linearization of the overall transmitter.

Different stages leading to the description of the IMC structure are introduced and illustrated by nonlinear simulation results. At first, a model is established to describe the behavior

of the transmitter and secondly a design of the nonlinear controller is presented. IMC is analyzed and compared to standard predistortion method trough simulation using *ADS software*.

II. INTERNAL MODEL CONTROL

IMC was originally developed for chemical engineering applications [14], and is considered as a robust control method. The IMC structure is shown in Fig. 1.

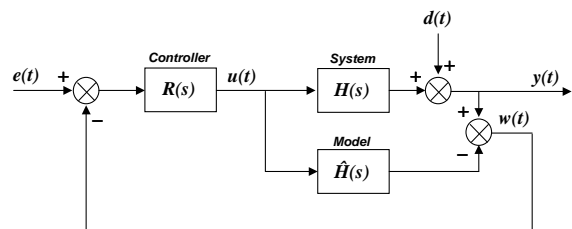


Fig. 1. Schematic of the IMC structure

The structure uses an internal model $\hat{H}(s)$ in parallel with the system to be linearized $H(s)$. The control loop is augmented by a block filter $R(s)$, so-called the *IMC controller*.

A. IMC analysis

The closed loop transfer function describing the input $e(t)$ and the disturbance $d(t)$ to output $y(t)$ relationship is given by:

$$Y(s) = \frac{R(s)H(s)}{1 + R(s)(H(s) - \hat{H}(s))} E(s) + \frac{1 - R(s)\hat{H}(s)}{1 + R(s)(H(s) - \hat{H}(s))} D(s) \quad (1)$$

The IMC loop computes the difference $w(t)$ between the system output $H(s)$ and the model output $\hat{H}(s)$. This residual signal $w(t)$ represents the effects of the disturbance $d(t)$ and of the modeling error between the model and the system. The IMC structure has advantages over conventional feedback control loop. If a perfect model is used, i.e. $\hat{H}(s) = H(s)$ there exists no feedback, and the closed loop system is affected only

by the disturbance $d(t)$. In this case, the closed loop system has the transfer function

$$Y(s) = R(s)H(s)E(s) + (1 - R(s)\hat{H}(s))D(s) \quad (2)$$

Noted that without disturbance the system is effectively open-loop hence no stability problems can arise. Also, if the system $H(s)$ is stable, which is the case for application to power amplifiers, the closed-loop will be stable for any stable controller $R(s)$. Furthermore, the controller can be designed as a feedforward controller in the IMC scheme.

An ideal control system, would suppress all disturbances and insure the instantly tracking of the input $e(t)$. From equation (2), the ideal control system is achieved for :

$$R(s)\hat{H}(s) = 1 \quad (3)$$

So, the ideal choice for the controller $R(s)$ is the model inverse $\hat{H}(s)^{-1}$. For the investigated application, the IMC must allow to compensate the static non linearity of the amplifier. The model of the system includes a model of the non linear static characteristic and the IMC controller includes the inverse static characteristic. If the inversion of the static characteristic model is perfect, the IMC scheme allows a rejection of the disturbance and of the non linearity effects.

B. Design procedure for PA linearization

The block diagram of IMC structure is shown in Fig. 2. All signal designations refer either to complex baseband signals and don't depend on the modulation format.

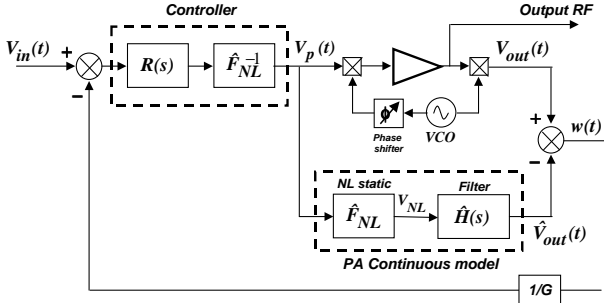


Fig. 2. Baseband equivalent scheme of the IMC structure

The proposed IMC structure allows linearizing the transmitter composed of the I/Q modulator, amplifier and demodulator blocks. The output of the demodulator is compared with the output of the baseband model of the amplifier and the resulting error signal $w(t)$, normalized according to PA gain G , is used to modify the input modulation signal.

The critical point in the IMC structure is the description of the inverse amplifier static nonlinearity. A solution consists in using a complex polynomial function, composed by even terms, to describe the inverse AM/AM and AM/PM characteristics. The main advantage of such models is that they are linear-in-parameters allowing Least Mean Square (LMS) estimation techniques.

III. BASEBAND PA CHARACTERIZATION

In IMC structure (Fig. 2), it is necessary to have a description of the process in continuous time domain. In this paper, a special case of Volterra series, the Hammerstein memory polynomial, is used.

A. PA model description

The nonlinear block presented here operates on baseband quadrature I/Q time-domain waveforms [8]. The complex low-pass equivalent representation of the communication signal is used to avoid the high sampling rate required at the carrier frequency.

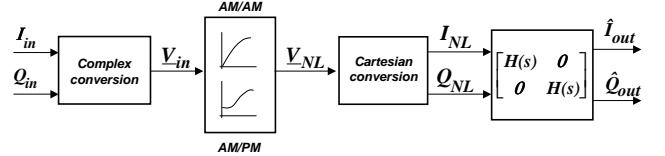


Fig. 3. Radio frequency power amplifier model

As shown in Fig. 3, the two-box model includes a memoryless nonlinearity and a Laplace filter matrix. The complex gain gives a nonlinear version $\underline{V}_{NL} = I_{NL} + j.Q_{NL}$ of the transmitted input signal $\underline{V}_{in} = I_{in} + j.Q_{in}$ according to the polynomial function composed by even terms which produces harmonic distortions inside the PA bandwidth:

$$\underline{V}_{NL} = \sum_{k=0}^P \underline{c}_{2k+1} \cdot |\underline{V}_{in}|^{2k} \cdot \underline{V}_{in} \quad (4)$$

where \underline{c}_{2k+1} are the complex power series coefficients.

The dynamical model including memory effects caused by the PA may be expressed with a differential equation. As shown in Fig. 3, the input \underline{V}_{NL} to output $\hat{\underline{V}}_{out} = \hat{I}_{out} + j\hat{Q}_{out}$ relation of this n^{th} order filter can be written as:

$$H(s) = \frac{\hat{I}_{out}}{I_{NL}} = \frac{\hat{Q}_{out}}{Q_{NL}} = \frac{\sum_{k=0}^m b_k \cdot s^k}{s^n + \sum_{k=0}^{n-1} a_k s^k} \quad (5)$$

where the coefficients $\{a_k\}$ and $\{b_k\}$ are real scalars that define the model.

B. Identification algorithm

The parameters a_k , b_k and \underline{c}_k of previous PA model have been identified by Output-Error technique (see also [15]). Thus, we define the transposed parameter vector:

$$\underline{\theta} = [a_0 \cdots a_{n-1} \ b_0 \cdots b_m \ \underline{c}_1 \cdots \underline{c}_{2P+1}]^T \quad (6)$$

As shown in Fig.4, we obtain the optimal values of $\underline{\theta}$ by Non Linear Programming techniques. Practically, Marquardt's algorithm [16] is used for the the minimization of quadratic criterion based on the error between measured data and estimation.

Identification results are shown on Fig.5 for a *MESFET power amplifier*, used at a center frequency of 900 MHz. The input signal is a pseudo random binary sequences (PRBS) at

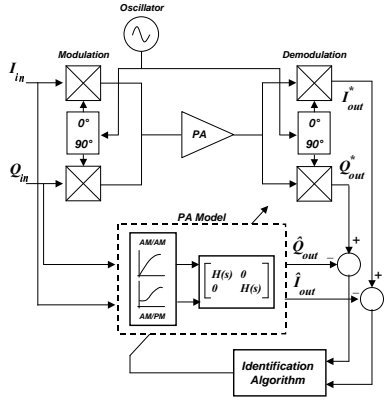


Fig. 4. PA identification scheme

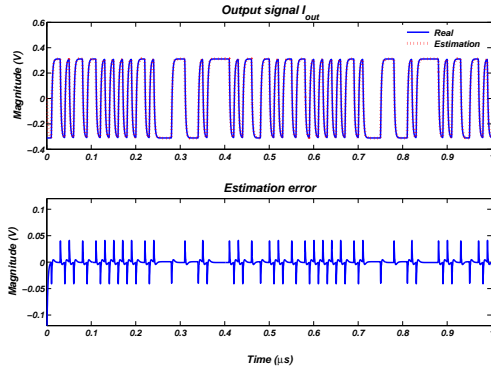


Fig. 5. Comparison of time-domain measurement and estimation

rate of 60 Mbits/s, filtered by a low pass root-raised cosine with $\alpha = 0.35$. For the amplitude and phase identification, third order polynomial expressions and 1st order filter $H(s)$ are used and allow achieving a good agreement between the amplifier behavior and its estimation.

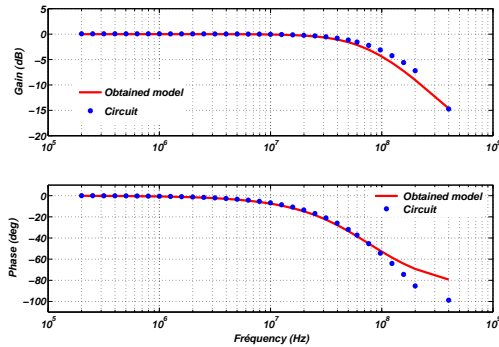


Fig. 6. Comparison between a frequency responses of the PA circuit and the obtained filter

The dynamic characteristic of the PA system can be described by a MIMO coupled filter. The real filter $H(s)$ and the obtained filter $\hat{H}(s)$ characteristics are represented in Fig. (6) by the gain and phase curves. The cut off frequency of the

corresponding filter is around 76 MHz.

IV. SIMULATION AND INVESTIGATION

The IMC structure is evaluated by nonlinear simulations using circuit envelope algorithm with Agilent ADS simulator. The described class AB PA presented in figure (7), is a single stage structure composed of a MESFET device by Infineon (CLY 5). The behavior of the transistor is described by a table based model of the nonlinear drain current source associated to a junction model for the gate to source capacitance.

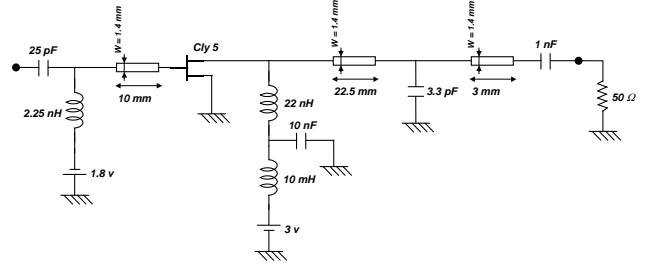


Fig. 7. PA circuit implemented on ADS software

The matching topology is designed to ensure optimum power and efficiency performances at the 900MHz operating frequency. The output matching has a low pass T structure composed of a capacitor to ground and two transmission lines.

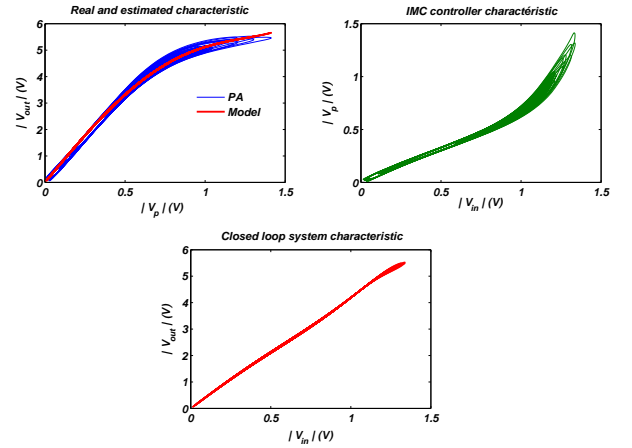


Fig. 8. Comparison of the dynamic envelope variations at the output of amplifier, model, controller and the dynamic AM/AM characteristic of the IMC system.

The input signal is a 16-QAM at a bite rate of 2.5Mb/s, modulated at 900 MHz and shaped with a raised-cosine pulse with 35%. This signal is applied to the IMC system. On Fig. 8 are presented the dynamic envelope variations of amplifier and model output, for such input signal. Also plotted are the dynamic envelope at the output of controller and of overall IMC system versus the instantaneous input envelope. This last curve allows to verify that the nonlinear behavior and the hysteresis effects are reduced, showing the interest of the IMC system.

Fig. 9 shows the output spectrum without linearization, with standard predistortion and with IMC linearizer for an output power backoff of 3 dB. Using IMC structure, an improvement of approximately 10dB is obtained according to standard predistortion and of 30dB according to PA without linearization.

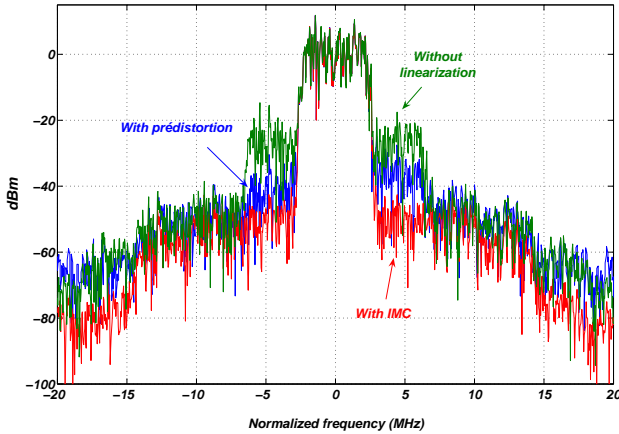


Fig. 9. Output spectrum for the amplifier without linearization, with predistorsion and with IMC.

Due to memory effects, linearization performances can depend on baseband signal frequency. To verify the performances of IMC, simulations have been performed for a two tones excitation with a difference of 2KHz to 20MHz between the carrier frequencies. Results are plotted on Fig. 10 in terms of carrier to third order intermodulation ratio C/I in dBc. For the standart predistorsion designed with the previous 2.5Mb/s 16-QAM modulation, performances are reduced and degraded at low baseband frequencies. Whereas, the IMC system allows to improve the nonlinear performances for the whole bandwidth considered.

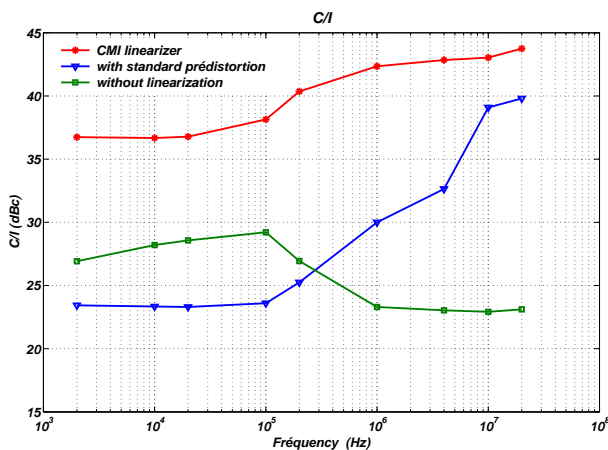


Fig. 10. Carrier to intermodulation ratio versus carrier frequency difference

V. CONCLUSION

In this paper, internal model control was introduced and applied to power amplifier linearization with different baseband signals. Design of the IMC system, using baseband signal, is described. Simulations are presented to demonstrate the interest of the technique. For a 16-QAM at a bite rate of 2.5Mb/s, IMC allows to reduce nonlinear and hysteresis effects on the dynamic envelope characteristic. Simulated performances show improvement of the ACPR of 30 dB for the amplifier at high output power, and 10 dB in comparison to predistorsion. Furthermore, IMC allows to improve performances in term of linerarity for different output levels and signal bandwidths.

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