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The Linearization of Multichannel Amplifiers Connected in Cascade with Enhanced Efficiency

Natasa Males-Ilic[1], Aleksandar Atanaskovic[2] and Bratislav Milovanovic[3]

***Abstract* – The linearization of the chain of three amplifiers connected in cascade has been performed in this paper. The second harmonics of the fundamental signals (IM2) together with the fourth-order nonlinear signals (IM4) are fed into the third amplifier in cascade. The linearization scheme is arranged so that the second amplifying stage is exploited as the source of IM2 and IM4 signals whereas the IM2 signals are extracted at the output of the first amplifier. The third amplifier in cascade operates as harmonic-controlled amplifier at class-A driven with half-sinusoidal signal. This configuration enables high gain of class A amplifier combined with higher-drain efficiency. Consequently, power-aided efficiency is increased as well as the suppression of the intermodulation products (third and fifth order) of amplifying system.**

***Keywords* – Multichannel amplifier, Intermodulation distortion, Linearization technique, Second harmonics, Saturation, Power-aided efficiency.**

I. INTRODUCTION

The linearization of multichannel amplifiers in base stations of wireless communication systems has always been of concern. The basic concept of the linearization technique with the injection of the second harmonics (IM2 signals) gives good results in reduction of the third-order intermodulation products, IM3, [1]-[3], up to the certain power of the fundamental signals that depends on load impedance [2]. The linearization technique that uses the injection of IM2 signals has been extended in [4] by introducing the injection of the fourth-order nonlinearity of the fundamental signals (IM4) in order to suppress the fifth-order intermodulation products (IM5) of a single amplifier.

In practice, the transmit path of microwave signals is usually composed of a chain of cascaded amplifiers to achieve sufficient output power and signal gain. The linearization concept considered in [5] investigates linearization of three amplifiers connected in cascade. In the concept, IM2 signals are driven into the second amplifier in cascade whereas IM2 and IM4 signals are put together (IM2+IM4) into the third amplifier. The fundamental signals are extracted at the output of the first amplifier in cascade and put to the nonlinear components biased at the appropriate points to generate the IM2 and IM2+IM4 signals.

In order to avoid two additional nonlinear components in the circuit for linearization, a new concept that uses IM2 and IM2+IM4 signals, which are generated at the amplifier stages, is considered in this paper.

II. THEORETICAL ANALYSIS

The linearization concept proposed in [5] shows remarkable results in the reduction of IM3 and IM5 products of the amplifying system consisting of three amplifiers connected in cascade. In order to simplify the linearization circuit and lower the number of additional components required for the linearization, the new concept is considered in this paper. Instead of the nonlinear transistors that are biased at appropriate point to produce IM2 or IM2+IM4 signals, those signals are extracted at the outputs of amplifiers in cascade as shown in Fig. 1. IM2 signals produced at the output of the first amplifier in cascade are combined with the IM2 and IM4 signals turn up at the output of the second amplifier that is biased at class B or AB to provide the sufficient power level of those signals. Adjusted in amplitude and phase resulting IM2+IM4 signals are put at the input of the third amplifier to achieve both the suitable drive signal for the amplifier [6] and to decrease the intermodulation products. Appropriate harmonic termination of the third amplifier that corresponds to class-F amplifier [7] gives the increase of drain efficiency accompanied with the high gain of class-A amplifier.

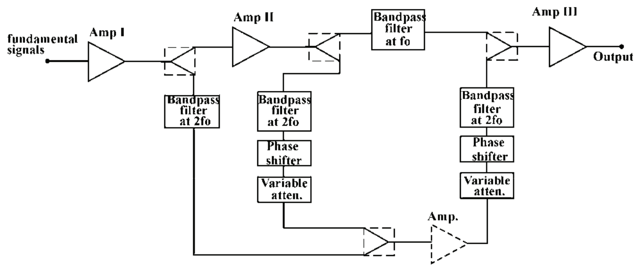


Fig. 1. Amplifying system with the additional circuit for linearization with IM2 and IM2+IM4 signals

Theoretical analysis of the proposed linearization approach is based on the nonlinearity of drain-source current expressed by a polynomial model [8], [9]. The expression for the nonlinearity of MESFET in amplifier circuit, under the assumption of neglecting the memory effect, is represented by eleven terms as given by (1). The drain-source current is dependent upon two control voltages: v_{gs}–voltage between

[1]Natasa Males-Ilic is with the Faculty of Electronic Engineering, Aleksandra Medvedeva 14, 18000 Nis, Serbia, E-mail: natasam@elfak.ni.ac.yu

[2]Aleksandar Atanaskovic is with the Faculty of Electronic Engineering, Aleksandra Medvedeva 14, 18000 Nis, Serbia, E-mail: beli@elfak.ni.ac.yu

[3]Bratislav Milovanovic is with the Faculty of Electronic Engineering, Aleksandra Medvedeva 14, 18000 Nis, Serbia, E-mail: bata@elfak.ni.ac.yu

gate and source and v_{ds}-voltage between drain and source of the transistor. The expression (1) connects the nonlinearity of the drain-source current, i_{ds}, in reference to voltage, v_{gs} that is represented by the coefficients $K_{10}^{(i)}$ to $K_{50}^{(i)}$. The higher order nonlinear terms $K_{40}^{(i)}$ and $K_{50}^{(i)}$ are included into the analysis according to the analysis performed in [10] that favors the terms of output current as function of v_{gs} up to the fifth-order.

The nonlinearity of drain-source current in terms of v_{ds} is expressed by the coefficients $K_{01}^{(i)}$ to $K_{03}^{(i)}$. In addition, the equation encompasses "mixing" terms $K_{11}^{(i)}$, $K_{12}^{(i)}$ and $K_{21}^{(i)}$.

$$\begin{aligned}i_{ds}(v_{gs},v_{ds}) &= K_{10}^{(i)}v_{gs}(t)+K_{20}^{(i)}v_{gs}^2(t)+K_{30}^{(i)}v_{gs}^3(t)+\\&+K_{40}^{(i)}v_{gs}^4(t)+K_{50}^{(i)}v_{gs}^5(t)+\\&+K_{01}^{(i)}v_{ds}(t)+K_{02}^{(i)}v_{ds}^2(t)+K_{03}^{(i)}v_{ds}^3(t)+\\&+K_{11}^{(i)}v_{gs}(t)v_{ds}(t)+K_{21}^{(i)}v_{gs}^2(t)v_{ds}(t)+K_{12}^{(i)}v_{gs}(t)v_{ds}^2(t)+\ldots\end{aligned} \tag{1}$$

A carrier supplemented with a baseband spectrum $V_B(j\omega)$ can represent the spectrum of a digitally modulated fundamental signal, $V_{infund}(j\omega)$, as given below:

$$V_{infund.}(j\omega)=V_B(j\omega)\otimes\frac{1}{2}\delta(\omega\pm\omega_0) \tag{2}$$

The spectrum of the IM2 signals at the output of the first amplifier can be expressed as follows:

$$V_{IM2}^{(1)}(j\omega)=\left\{K_{20}^{(1)}\left[V_B(j\omega)\otimes V_B(j\omega)\right]\right\}\otimes\frac{1}{4}\left(\delta(\omega\pm 2\omega_0)\right) \tag{3}$$

The second amplifier produces the IM2 and IM4 signals which spectrum is expressed as:

$$\begin{aligned}&V_{(IM2+IM4)}^{(2)}(j\omega)=\\&\left\{\left(K_{10}^{(1)2}K_{20}^{(2)}+K_{20}^{(1)}K_{10}^{(2)}\right)\rho_{23}e^{-j\varphi_{23}}\left[V_B(j\omega)\otimes V_B(j\omega)\right]\right\}\\&\otimes\frac{1}{4}\left(\delta(\omega\pm 2\omega_0)\right)\\&+\left\{\left(K_{10}^{(1)2}K_{20}^{(1)}K_{10}^{(2)}+K_{10}^{(1)}K_{30}^{(1)}K_{20}^{(2)}+K_{10}^{(1)4}K_{40}^{(2)}+K_{40}^{(1)}K_{10}^{(2)}\right)\right.\\&\left.\rho_{43}e^{-j\varphi_{43}}\left[V_B(j\omega)\otimes V_B(j\omega)\otimes V_B(j\omega)\otimes V_B(j\omega)\right]\right\}\\&\otimes\frac{1}{4}\left(\delta(\omega\pm 2\omega_0)\right)\end{aligned} \tag{4}$$

Nonlinearity of the second order in the second amplifier (term $K_{20}^{(2)}$) mixes two linearly amplified fundamental signals of the first amplifier giving the first term in (4). Additionally, the second term stands for signals produced due to the second order nonlinear term in the first amplifier, $K_{20}^{(1)}$, which is linearly amplified by the second amplifier. Besides those IM2 signals, the expression (4) contains terms that relates to the IM4 signals (third to sixth terms). One can notice that they are products of nonlinear terms of first to fourth order, $K_{10}^{(i)}$ - $K_{40}^{(i)}$ i=1,2, in transfer characteristic of both first and second amplifiers. The amplitude and phase of IM2+IM4 signals from the second amplifier are adjusted to reach the required power level when combine with the IM2 signals from the output of the first amplifier. Signals obtained in this way are led to the input of the third amplifier. To approach the optimum power level of IM2 and IM4 signals for the linearization they should be set on adequate amplitude and phase throughout the injection path. Parameters ρ_{23} and φ_{23} represent amplitude and phase of the IM2 signal driven at the input of the third amplifier, whereas ρ_{43} and φ_{43} relate to the same parameters when IM4 signal is considered.

The drain-source current of the IM3 and IM5 products at the output of the third amplifier is given by (5), and (6) where the coefficients $K_{10}^{(1,2)}$ to $K_{50}^{(1,2)}$ are treated as dominant nonlinerities of the chain of the first and second amplifier in cascade. The coefficients $K_{10}^{(3)}$ to $K_{50}^{(3)}$, $K_{11}^{(3)}$ and $K_{21}^{(3)}$ characterize the third amplifier.

$$\begin{aligned}I_{ds}(j\omega)\big|_{IM3}\approx&\left\{\left[\frac{3}{4}K_{30}^{(1,2)}K_{10}^{(3)}+\frac{3}{4}K_{10}^{(1,2)}K_{30}^{(3)}+\right.\right.\\&\left.+\frac{1}{4}K_{10}^{(1,2)}K_{20}^{(3)}\rho_{23}e^{-j\varphi_{23}}-\frac{1}{4}K_{10}^{(1,2)}K_{11}^{(3)}\rho_1\rho_{23}e^{-j\varphi_{23}}\right]\\&\left.V_B(j\omega)\otimes V_B(j\omega)\otimes V_B(j\omega)\right\}\otimes\frac{1}{2}\delta(\omega\pm\omega_0)\end{aligned} \tag{5}$$

$$\begin{aligned}I_{ds}(j\omega)\big|_{IM5}\approx&\left\{\frac{5}{8}K_{50}^{(1,2)}K_{10}^{(3)}+\right.\\&+K_{10}^{(1,2)}\left[\frac{5}{8}K_{50}^{(3)}+\frac{1}{4}K_{20}^{(3)}\rho_{43}e^{-j\varphi_{43}}-\frac{1}{4}K_{11}^{(3)}\rho_1\rho_{43}e^{-j\varphi_{43}}+\right.\\&\left.+\frac{1}{8}K_{30}^{(3)}\rho_{23}^2e^{-j2\varphi_{23}}-\frac{1}{8}K_{21}^{(3)}\rho_1\rho_{23}^2e^{-j2\varphi_{23}}\right]\\&\left.V_B(j\omega)\otimes V_B(j\omega)\otimes V_B(j\omega)\otimes V_B(j\omega)\otimes V_B(j\omega)\right\}\otimes\frac{1}{2}\delta(\omega\pm\omega_0)\end{aligned} \tag{6}$$

In (5) the first term relates to the IM3 products of the first and second amplifiers linearly transmitted by the third amplifier. The second term exists due to the cubic nonlinearity of the third amplifier that mingles fundamental signals. The term at the third place in the equation is made due to square nonlinearity of Amp. III, $K_{20}^{(3)}$, that mixes the fundamental signal with IM2 signal. The fourth term relates to the mixing product $K_{11}^{(3)}$ gained by interaction between IM2 signal at the input of the third amplifier and fundamental signal come out at its output. The amplitude of output voltage at fundamental signal frequency that is 180° out of phase in reference to the input signal is denoted as ρ_1.

According to this, it is possible to reduce spectral regrowth caused by third-order distortion of fundamental signal by choosing the appropriate amplitude and phase of the injected

IM2 signal (ρ_{23} and φ_{23}). Depending on the input signals' power and values of $K_{20}^{(3)}$ and $K_{11}^{(3)}$ coefficients, the fourth term may constrain the linearization effect, having the phase opposite to the third term in (5).

The first term in (6) represents IM5 products of the chained the first and second amplifiers, that are linearly amplified by the third amplifier in cascade. The second term expresses the drain-source current of the IM5 products that is formed due to the existence of fundamental signals and amplifier nonlinearity of the fifth-order, $K_{50}^{(3)}$. The third term is the mixing product between the fundamental signal and IM4 signal fed at the input of the third amplifier. Also, IM5 products are formed by $K_{11}^{(3)}$ term that stirs IM4 signals led at the input of the third amplifier and fundamental output signal. The IM5 products are also a function of $K_{30}^{(3)}$ mixing term made by a reaction between two IM2 signals and fundamental one. Mixing term which stands by $K_{21}^{(3)}$ in (6) is generated due to reaction between two IM2 signals at the third amplifier input and fundamental signal at its output. Since IM2 and IM4 signals that appear at the output of third amplifier are shortened (according to harmonic terminations in class-F amplifier) the other $K_{12}^{(3)}$ and $K_{21}^{(3)}$ terms do not exist.

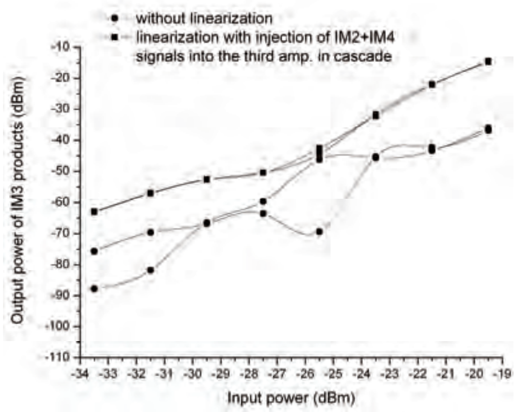
It is obvious that for the larger amplitudes of the fundamental signals the injected IM2 signals are supposed to have greater amplitudes as well according to (5). Since φ_{23} is to be equal to 180° to reduce IM3 products, the phase of the $K_{30}^{(3)}$ term in (6) is 360°. Accordingly, with the rise in amplitudes of IM2 signals, mixing $K_{30}^{(3)}$ term (the fifth term in (6)) starts increasing the power of IM5 spectrum. Due to the overlapping of IM3 and IM5 spectra the power augmentation in the range of IM3 spectrum is unavoidable. The influence of the fifth term to the power of IM3 and IM5 products can be cancelled by the sixth term.

Therefore, by adjusting the amplitude and phase of the appropriate IM4 signal the original IM5 product (the first and second terms) can be reduced. As is the case in (5), the raise in power levels of the IM2 and IM4 signals fed at the amplifier input are limited by $K_{11}^{(3)}$ term in (6) that is opposite in phase to $K_{20}^{(3)}$ term.

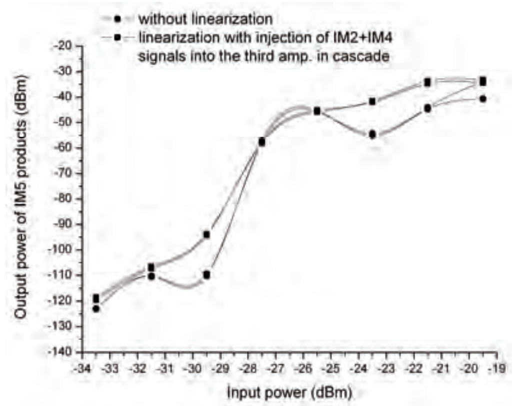
Proposed linearization concept can be applied to boost the drain efficiency of the third amplifier. This stage operates at class-A driven with half-sinusoidal signal that can be considered as the fundamental signal influenced by the second harmonics (IM2). By setting amplitude and phase of IM2 signals on appropriate values the shape of half-sinusoidal signal is control so that the third stage harmonic-controlled amplifier, [10], attains high-drain efficiency combined with high gain of class-A amplifier. Consequently, power-aided efficiency is increased in reference to class F-amplifier.

III. Simulated Results for the Second Linearization Concept

The configuration of amplifying system consists of three amplifiers as depicted in [5]. However, in this paper the third amplifier is terminated at second harmonics (IM2 signals) and third harmonics as class-F amplifier but biased at class-A. Fig. 2 illustrates the reduction of IM3 products at frequencies 2.49 GHz and 2.52 GHz and IM5 products (2.48 GHz and 2.53 GHz) in case of two fundamental signals at the input of amplifying system, 2.5 GHz and 2.51 GHz. It follows from the figure that the suppression of IM3 products is not equal for both IM3 products in entire power range of input power observed. At the points where optimization is performed, (-29 dBm and -21 dBm), IM3 products is approximately 10 dB and 20 dB lower than before linearization, respectively. As far as IM5 products are concerned, the results are worse than those gained by the linearization concept described in [5] that also uses IM2 +IM4 signals. However, the linearization concept proposed here includes the linearization circuit of less complexity enabling satisfactory results for IM3 products in the large range of the input power going up to the higher power levels close to saturation point.



a)



b)

Fig. 2. Output power in terms of the input power before and after linearization for: (a) IM3 products; (b) IM5 products

In the case when the third stage is class-F amplifier the maximum negative gate voltage ascends to double of half-sinusoidal driven class-A harmonic control amplifier so that it is necessary to rise the input power of fundamental signals in order to achieve the same output power. It is obvious that the class-A amplifier in the third stage provides the higher gain and output power than class-F amplifier; therefore, the power-aided efficiency (PAE) is improved in reference to the class-F case by 3 % observed at -19 dBm input power.

Additionally, the designed amplifying system has been tested for three sinusoidal fundamental signals at frequencies 2.5 GHz, 2.51 GHz and 2.522 GHz when the power of fundamental signals at the input of amplifier is –23 dBm that is 5 dB below 1-dB compression point of the third amplifier. The output spectra consisting of the fundamental signals, IM3 and IM5 products are compared in Fig. 3 for the cases before and after linearization. Various results are gained for different kinds of IM3 and IM5 signals. For example, IM3 products at frequencies $2\omega_i$-ω_j (the first kind) are lowered by 18 dB whereas they are approximately reduced by 15 dB at frequencies $\omega_i+\omega_j-\omega_k$ (the second kind) $i \neq j \neq k \in (1,2,3)$. It follows from Fig. 3 that all IM5 products are kept at the lower or nearly equal power level to the linearized IM3 products.

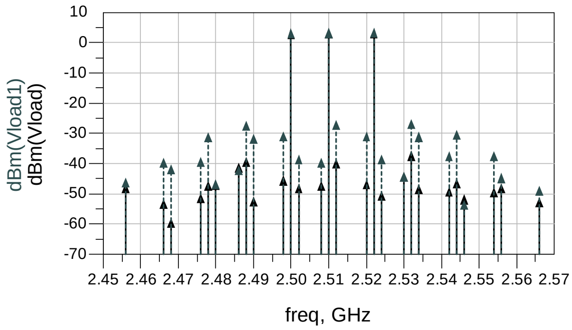


Fig. 3 Output spectrum before and after linearization for three fundamental sinusoidal signals

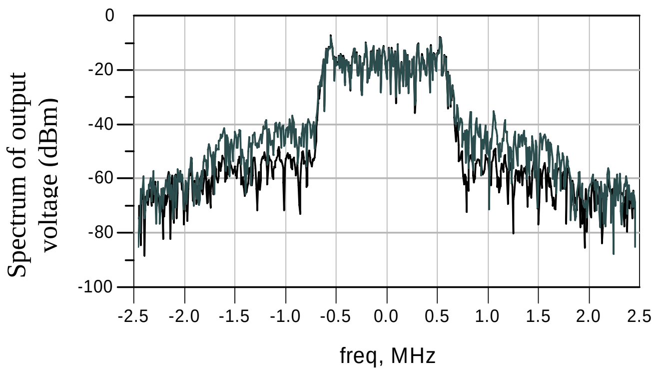


Fig. 4. Simulated spectrum of the output voltage for OQPSK digitally modulated signal before (grey line) and after linearization (black line) with the second concept for -19 dBm carrier input power

On the top of that, the amplifying system has been tested for OQPSK digitally modulated signal at carrier frequency 2.5 GHz and spectrum width 1.25 MHz. The results shown in Fig.4 compare the output spectra before and after the linearization for -19 dBm power levels of the fundamental signals. Improvement observed at ±900 kHz offset from the carrier over the 30 KHz frequency range is 11 dB whereas the ACPR at offset ±2.1 MHz becomes better for 4 dB.

IV. Conclusions

The new linearization concept of the amplifiers in cascade has been considered in order to simplify the linearization circuit. The linearization is based on the injection of the second harmonics (IM2 signals) and fourth-order nonlinear signals (IM4). IM2 and IM2+IM4 signals are extracted at the outputs of amplifiers in cascade and combined. When adjusted in amplitude and phase they are injected at the input of the third amplifier in cascade. It should be pointed out that the linearization circuit of less complexity reaches remarkable reduction of IM3 products for configuration of amplifying system which enables high power-aided efficiency. Injected IM2 and IM4 signals are adjusted not only to achieve the highest possible PAE but also to lower the IM3 and IM5 products, so the achieved results represents the compromise between the excellent results for both PAE and IM products simultaneously.

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