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The Linear Behavior Analysis of Class D Power Amplifier

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ABSTRACT

This paper deals with linear behavior and distortion of class-D amplifier. Calculation approach and effective terms on the distortion of amplifier is also carried out. The typical circuit of class-D amplifier CMCD is considered. Traditional approaches have been analyzed the distribution amount in class-D amplifier in voltage mode (VMCD) simulation result has been compared with mathematical approaches of amplifier. This comparison validates the effectiveness of mentioned terms on third harmonic distortion amounts.

KEYWORDS: RF Circuit, Class-D power Amplifier, Third-Order Harmonic Distortion.

1. INTRODUCTION

RF power amplifiers are the most commonly used RF transmitter section. RF circuits have to process analog signals with high dynamic range and in high frequency. Due to some problems of ordinary linear power amplifier (A, B, AB) including high heat losses and the need for high-volume endothermic, the trends toward switching amplifiers and special type of Class D are increased. This amplifier was first proposed by an English inventor Clive Sinclair in 1964 [1]. Class D power amplifier is used as switching in transmitters, wireless and cellular receivers, portable DVD Players, speakers with USB ports, notebooks and portable computers. Class D amplifier does strengthening act at high frequencies ranging from HF to VHF, it means about 300 KHz to 300 MHz. High-Efficiency Power Amplifier D is a kind of power amplifier that its efficiency is more than the conventional efficiency of class A, B or C amplifiers used in similar circumstances. Class D amplifier, unlike class A, B, AB and C amplifiers, yields a One hundred percent of the theoretical efficiency [2]. The transistor acts as a switch in Class D power amplifier to minimize the transistor's losses. This will happen in such a way in which transistors are connected in a part of the alternation period and disconnected in another section, this type of circuit is called a switching mode power amplifier because the two active ingredients are used in such a way that they are on or off alternatively. Also, if it is assumed that switching devices are ideal, the amplifier's casualties will be zero. According to today's technology need in using of an amplifier with maximum efficiency and low loss, the use of this amplifier is justified [1]. Efficiency has greatly increased in portable systems of this class, but rather these amplifiers are non-linear. One of the most important properties of Class D Power Amplifier is power consumption, efficiency, and nonlinear behavior. Linearization techniques are divided into two categories: system level and circuit level in which the former includes the removal and recycling techniques such as cover, feed forward, feedback, etc, and the latter includes circuits that can neutralize or improve the effect of the present nonlinear elements in the power amplifier. The nonlinear behavior of amplifiers, in other words the third order harmonic distortion, needs to be improved and analyzed. Transformers were the first recognized harmonic sources and then grand stood in the phone systems. However the harmonic distortion in power amplifier is more important. Great efforts are done to analyze the distortion and amplifier linear behavior caused by the third order harmonic. Distortion analysis is calculated by different techniques. The Taylor series is used to calculate the distortion in nonlinear circuits [3]. Classic power amplifiers as well as A and B amplifiers raises the distortion rate to <0.1% [4]. The systemic done ways suggest that the improvement of the distortion and HD_3 is realized by using feedback closed loop. Also by adding several feedback loops and changing it into the multi-floor circuit, the HD_3 values can easily be improved in comparison to the open-loop circuit [5] [6]. In circuit analysis, the review and analysis of nonlinear amplifier has been done by using Fourier series [7] [8]. In another report, the harmonic distortion with the analysis of Dead Time mode or switching dead time between two switching transistors and its impact on the harmonica has been studied [9]. This article is investigated to analyze the third order harmonic distortion by using the transistors governing relationship and utilizing Taylor series. This paper is organized in 6 sections. The flow mode class D power amplifier is introduced in next part of this article. The third section introduces HD_3 third order harmonica distortion and a proposed method is presented in section 4 to analyze HD_3. To make valid the provided analysis, the simulation results are presented in section V and finally, the article's conclusion is presented in section VI.

2. CLASS D POWER AMPLIFIER

2.1. INTRODUCTION

High-efficiency power amplifier is a power that its efficiency is greater than the efficiency of conventional class A, B or C amplifiers used in the same conditions. The high efficiency of these amplifiers is the result of the ways that change the average product of flow voltage collector to the minimum. This goal is achieved in the switching amplifiers (class D, E and S) by using active elements as a key. Due to the fact that either voltage or current is zero in ideal key, so no power is consumed. Special circuit techniques, including harmonic resonator and a multi-voltage power supplies are used in other high-efficiency amplifiers (class F, G and H) to reduce the voltage-current product. Of course the high-efficiency amplifiers are made of the actual active ingredients so they are subject to the effects of saturation voltage and resistance, scattered reactance and non-zero time off, all of these effects reduce the efficiency of the amplifier less than the ideal value. Depending on to what extent the shape of the waves are close to a square wave shape, the output will also be close to 1 or 100%.Class D power amplifier consists of two transistors which can operate in two different modes. Depending on the outlet filter arrangement (tank), the amplifier is divided into two types of voltage mode (VMCD[1]) and current mode (CMCD[2]). If the LC resonance circuit is connected in series with the load and the bias voltage is constant, the system uses voltage mode. In 2001, Class D amplifier current mode was suggested, built and tested. The current waveform is in squared shape and the voltage is in half-sinus mode. CMCD architecture has more advantages over class E, F amplifiers and Class D voltage mode. CMCD has maximum operating frequency and maximum power output performance benefits. For a transistor, CMCD produces more power than any other design (equal to the voltage mode). Moreover, there is no fundamental limit for the parallel capacitor value in CMCD when it includes tank circuit. The interaction which should be considered is the interaction between Q tank and the output power in too large devices. Traditional Class D amplifiers (VCMD) suffer from several problems that make it difficult to realize them, especially at high frequencies. First, the availability of suitable apparatus is limit for a high frequency switch. Second, the parasitic devices such as drain - source and self capacitors are caused losses amounting to 1/2 cv2 or 1/2 li2 in each cycle. Class D amplifiers can theoretically reach to 100% efficiency in low and sound frequencies, for example there is no period during a cycle in which there is a interference between flow wave shape and voltage [10]-[13].

2.2 The Introduction of Flow Mode Class D Power Amplifier

This amplifier was first suggested by Baxandll. Class D power amplifier is shown in (1) and the voltage and current curves are shown in Figure 2. The current source is used instead of the voltage source in CMCD circuit and two switching transistors control current instead of voltage. There is a parallel filter with a set resonance at the carrier frequency output. Because of the resonance of the filter, transistors voltage decline is zero at switching time. Another switching condition, which is less important, prevents inductor losses by creating zero current at the switching moment. Another advantage of CMCD amplifier is its easy use at high frequencies. VCMD amplifier usually requires split complementary components or transformer for proper operation but CMCD amplifier requires only a simple structure tank. This tank circuit includes a low pass filter that removes the square waveform harmonica and converts the output to sinus. The load circuit is also a parallel resonance circuit set in switching frequency [10]-[13].

3. THE THIRD ORDER HARMONIC DISTORTION HD_3

Harmonic distortions are frequencies that are not present in the input signal to the amplifier and the origin of this type of distortion is in the amplifier. This distortion is caused by dynamic nonlinear elements. Although the distortion sometimes happens randomly in the systems, but it appears periodically in most cases. That means successive cycles are almost the same and may slowly change. This concept describes the harmonic terms. Harmonic distortion is caused by nonlinear elements which convert the linear system into a nonlinear system. Linear system is a kind of system that its output can be expressed in a state of a single

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[1] Voltage Mode Class D
[2] Current Mode Class D

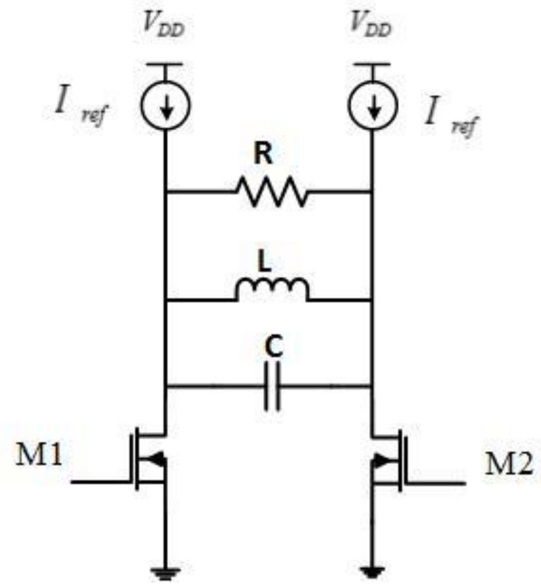

Fig. 1. current mode class D power amplifier circuit

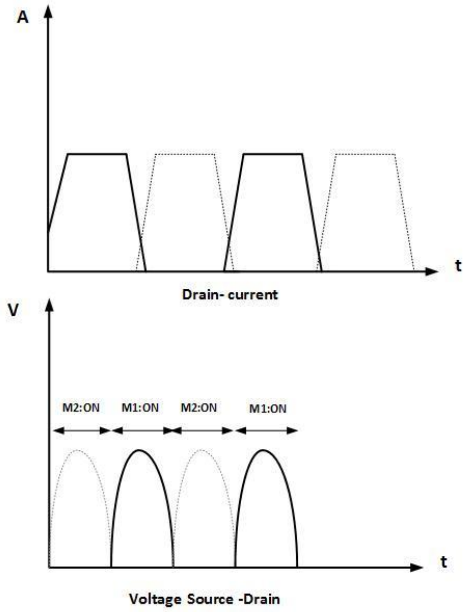

Fig 2. current waveforms and CMCD circuit voltage

linear combination of its response to every the input. More specifically, if for the inputs x1 (t) and x2 (t) we have:

$x_1(t) \rightarrow y_1(t)$ و $x_2(t) \rightarrow y_2(t)$

So for all the constants a and b, we have:

$$ax_1(t) + bx_2(t) \rightarrow ay_1(t) + by_2(t) \qquad (1)$$

Any system that does not make the above condition happens, is nonlinear. Nonlinear characteristic often leads to interesting and important phenomena. One of these phenomena is the harmonic distortion. The system is introduced by the following equation:

$$y(t) = a_1x(t) + a_2x^2(t) + a_3x^3(t) \qquad (2)$$

If a sinusoidal applied to nonlinear system, the output will usually have frequency components that their frequency is correct coefficient of the input frequency. In equation (2) if x (t) = Acosωt then:

$$y(t) = \alpha_1 A\cos\omega t + \alpha_2 A^2\cos^2\omega t + \alpha_3 A^3\cos^3\omega t = \alpha_1 A\cos\omega t + \frac{\alpha_2 A^2}{2}(1 + \cos 2\omega t) + \frac{\alpha_3 A^3}{4}(3\cos\omega t + \cos 3\cos\omega t) = \frac{\alpha_2 A^2}{2} + \left[\alpha_1 A + \frac{3\alpha_3 A^3}{4}\right]\cos\omega t + \frac{\alpha_2 A^2}{2}\cos 2\omega t + \frac{\alpha_3 A^3}{4}\cos 3\omega t \qquad (3)$$

In equation (3) a statement that has the main frequency is named main component and the above sentences is named harmonica. The sentences with even square make even harmonics, and the sentences with odd square make the odd harmonics. It is noteworthy that the nth harmonic increases roughly in proportion to the nth input. This effect is called harmonic distortion.[1] Expansion of the equation (3) can be used to calculate the amount HD_3.

$$HD_3 = \frac{\frac{\alpha_3 A^3}{4}}{\alpha_1 A} = \frac{1}{4}\frac{\alpha_3}{\alpha_1}A^2 \qquad (4)$$

4. THE PROPOSED METHOD FOR CALCULATING HD3

Considering the circuit works in switching mode so one of the transistors is always in On state and the other is in Off state. In order to calculate the harmonica distortion, we use half circuit. Due to the non-linear circuit for calculation of HD_3, power series and Taylor series analysis and its coefficients are used [3].
Taking into account the channel length modulation

$$V_o = H_o + H_1V_i + H_2V_i^2 + H_3V_i^3 + \cdots \qquad (5)$$

$$\begin{aligned} i_0 &= K(V_{GS} - V_{th})^2(1 + \lambda V_{DS}) = \\ &K(V_i + V_G - V_{th})^2(1 + \lambda V_o) = \\ &K(V_i + V_{od})^2(1 + \lambda V_0) \end{aligned} \qquad (6)$$

$$V_o = -i_oZ_L = -K(V_i + V_{od})^2(1 + \lambda V_o)Z_L \qquad (7)$$

Considering:

$$K = \mu_n C_{ox}(W/L) \qquad (8)$$

And assuming

$Z_L = R \quad , V_{od} = V_G - V_{th}$

Where L, W are the width and length of the transistor, Cox oxide capacitance per channel area and in the mobility rate of the minority field carrier.
Therefore :

$$V_o = -K\left(V_i{}^2 + V_{od}{}^2 + 2V_iV_{od}\right)(1 + \lambda V_o)R = -KV_{0d}^2R - 2KV_{od}RV_i - KRV_i^2 + \lambda V_0(-KV_{od}^2R - 2KV_{od}V_iR - KRV_i{}^2) \qquad (9)$$

Assuming that:

$$D_0 = -KV_{od}^2R \ , D_1 = -2KV_{od}R \ ,D_2 = -KR$$

we get

$$V_o = H_o + H_1V_i + H_2V_i^2 + H_3V_i^3 = D_0 + D_1V_i + D_2V_i^2 + \lambda D_0(H_o + H_1V_i + H_2V_i^2 + H_3V_i{}^3) + \lambda D_1(H_o + H_1V_i + H_2V_i^2 + H_3V_i{}^3)V_i + \lambda D_2(H_o + H_1V_i + H_2V_i^2 + H_3V_i{}^3)V_i^2 \qquad (10)$$

$$H_o = D_0 + \lambda DH_0 \quad , \quad H_o = \frac{D_o}{1-\lambda D_0} H_o = \frac{-KV_{od}^2R}{1+\lambda(KV_{od}^2R)} \qquad (11)$$

$$H_1 = D_1 + \lambda D_oH_1 + \lambda D_1H_0 \quad , \quad H_1\,(1 - \lambda D_0) = D_1(1 + \lambda H_0), \quad H_1 = \frac{D_1(1+\lambda H_0)}{(1-\lambda D_0)} \qquad (12)$$

$$H_1 = \frac{-2KV_{od}R(1+\lambda(\frac{-KV_{od}^2R}{1+\lambda\left(KV_{od}^2R\right)})}{1+KV_{od}^2R}$$

$$H_2 = D_2 + \lambda D_0H_2 + \lambda D_1H_1 + \lambda D_2H_0 \quad , \quad H_2 = \frac{D_2+\lambda D_1H_1+\lambda D_2H_0}{1-\lambda D_0} = \frac{D_2+\lambda(D_1H_1+D_2H_0)}{1-\lambda D_0} \qquad (13)$$

$$H_3 = \lambda D_0H_3 + \lambda D_1H_2 + \lambda D_2H_1 \quad , \quad H_3 - \lambda D_0H_3 = \lambda D_1H_2 + \lambda D_2H_1 \quad , \quad H_3 = \frac{\lambda D_1H_2+\lambda D_2H_1}{1-\lambda D_0} = \frac{\lambda(D_1H_2+D_2H_1)}{1-\lambda D_0} \qquad (14)$$

Due to the high computations and equation (4) HD3 is obtained from the following equation:

$$\mathrm{HD}_3 = \frac{1}{4}\frac{H3}{H1}A^2$$

$$\mathrm{HD}_3 = \frac{1}{4}\frac{\frac{\lambda(D_1H_2+D_2H_1)}{1-\lambda D_0}}{\frac{-2KV_{od}R(1+\lambda(\frac{-KV_{od}^2R}{1+\lambda\left(KV_{od}^2R\right)})}{1+KV_{od}^2R}}A^2 \qquad (15)$$

5. SIMULATION RESULTS

CMCD circuit in figure 1 is simulated by using HSPICE software. By comparing the graphs, it can be concluded when the resistance increases, the harmonic rate is reduced. In resistance of 300 ohms, HD_3 measuring for simulation model and circuit analysis are exactly to the extent that are shown in Figure 3 and Table 2. Comparing the obtained mathematical equations to simulation result shows that the HD_3 rate depends on the tank resistance (R). Simulation of different resistance per tank is made for more verification of the validity of analyzed calculations. Simulation analysis is based on data from Table 1

Table 1. CMCD Parameters of the simulation

parameter	Simulation	unit
RLC Tank Specification		
R	0.3KΩ	KΩ
C	60PF	PF
L	2nH	nH
Transistor Specification		
W	10.3	μm
L	0.38	8μm
I_{ref}	500	μA
	10.3	μm
technology	0.18	μ

6. CONCLUSIONS

In this article, analyzing of the amplifier was studied first. Then the mathematical equations governing the third order harmonica distortion is calculated by using the Taylor series analysis. In this paper an attempt has been made to provide the suitable mathematical equation for calculating HD_3 so, the designers can benefit from it to achieve the desired characteristics. In order to better evaluation, the circuit is simulated for different values of the circuit parameters and by using of HSPICE software. It can be seen that by varying the tank resistance, HD_3 rate changes too. Closeness of the analytical results and the simulation confirms the accuracy of the proposed method.

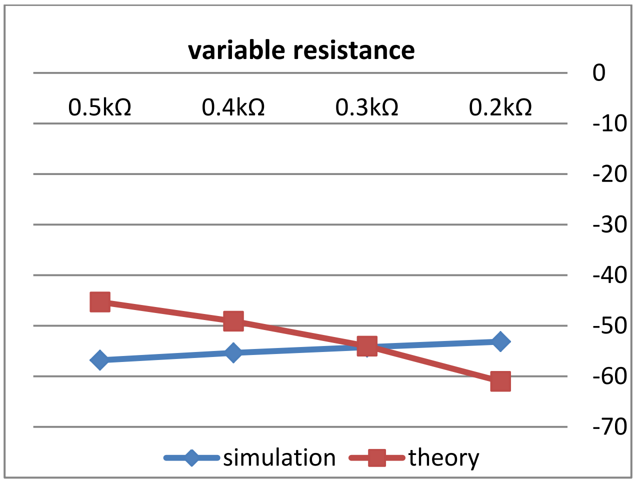

Fig. 3. HD$_3$ values for variable resistance in W =10.3, L = 0.38

Table 2. HD$_3$ values for the variable resistance in W = 10.3 and L = 0.38

R	a_1	a_3	HD$_3$	
			theory	simulation
200Ω	144.03u	65.51m	-53.15	-60.98
250Ω	143.05u	69.78m	-53.76	-57.14
300Ω	141.10u	72.44m	-54.2	-54.01
350Ω	136.56u	74.15m	-54.6	-51.38
400Ω	128.07u	74.96m	-55.34	-49.09
450Ω	120.30u	75.57m	-55.96	-47.09
500Ω	109.24u	75.77m	-56.82	-45.30

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