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Design of a Three-Way Doherty Power Amplifier for Base-Station Applications

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***Abstract*— The Doherty Power Amplifier (DPA) is used in a base station for mobile system (W-CDMA and 3G) because of its high efficiency. This paper presents the design and operation behavior of three-way Doherty amplifier. The amplifier is designed in the configuration with two quarter-wave impedance transformers in the output combining circuit and with GaAsFET device in carrier and peaking amplifies. The class AB power amplifier used in the configuration of the carrier amplifier. The class C is used in the configuration of the peaking amplifiers. The results obtained shows that three-way DPA can be used in wide-band spectrum. The amplifier works at 2.14GHz and has very good power added efficiency (PAE %), gain and output power at output back-off regions (OBO) (-6dBm, -9.54dBm and -12dBm) below maximum output power compared with classical DPA and conventional power amplifier type Class AB. The 3-way DPA can also work at different frequencies for input power greater than 20dBm.**

***Index Terms*—N-Way Doherty power amplifier (N-Way DPA), classes amplifier, Base-station, linearization, power added efficiency and output back-off points.**

I. INTRODUCTION

Mobile communication has become quite common in today's world with the increasing needs of effectively utilized bandwidth, and efficient and compact device technologies. The growth of wireless technologies is extremely fast. The information can be easily communicated by mobile communication system such as third generation Wide-Band Code Multiple Access (W-CDMA).More than ever, the modern wireless communication industry has increased interest for the high-efficient and linear amplifiers to accommodate current communication standards. The third generation (3G) and beyond communication standards offer high data rate transmission and transmit power that carries high-peak-to-average ratio signals. Therefore, base-station amplifiers operate most of their time at lower power level than their maximum, which consequently degrades the efficiency. The Doherty amplifier that is capable of achieving the requirements of the power amplifiers in base station concerning high efficiency becomes attractive for wireless industry [1]. In order to reduce the Auxiliary device size, while still providing the required current for the load modulation, a different solution is based on the so called Multi-Way Doherty configuration, usually referred as N-Way Doherty amplifier. It is realized by paralleling one Main amplifier and N-1 Auxiliary amplifiers [2].

The linearization of three-way Doherty amplifier in configuration with one quarter-wave impedance transformer in the output combining circuit and with LDMOSFETs in carrier and peaking amplifies in periphery relations 1:1:1 was considered in paper [3]. The linearization approach mentioned above achieved very good results in the reduction of both IM3 and IM5 products retaining the high efficiency of Doherty amplifier.

The work presented in [4] explores three-way Doherty 100-W GaN base-station power amplifier at 2.14 GHz. Simple, but accurate design equations for the output power combiner of the amplifier are introduced. Mixed-signal techniques are utilized for uncompromised control of the amplifier stages to optimize efficiency, as well as linearity. The combination of the above techniques resulted in an unprecedented high efficiency over a 12-dB power back-off range, facilitating a record high power-added efficiency for W-CDMA. The results obtained by authors are PAE% about (53%) at 0dBm output power back-off (OBO) and (33%) at -6dBm and (21%) at -9.54dBm.

The authors of paper [5], mainly deal with 3-way asymmetric Doherty Power Amplifier (ADPA) using two asymmetric devices with a new output combining circuit. This ADPA has an advantage for easy of implementation with large matching tolerance, compared to the conventional output combining circuits. This ADPA delivers a saturated output power of 51.7 dBm and a drain efficiency of 60.4% at an average output power of 43.6 dBm, which is 8.1 dB back-off from the peak power, and satisfies the linearity specification with -51.98 dBc ACLR at 10MHz offset after linearization. The results obtained by authors that the proposed ADPA delivers high efficiency and good linearity for the modulated signal with a high PAPR.

In this paper three-way Doherty amplifier in the configuration with two quarter-wave impedance transformers in the output combining circuit and with GaAsFET device in carrier and peaking amplifies. The output impedances of the amplifier cells are selected to satisfy the output power relations between the carrier and peaking cells. In this work an Advanced Design System (ADS) software has been used to design the RF amplifier type three-way DPA with high efficiency and high linearity. The results obtained are very good compared with two-way DPA and conventional power amplifier (Class AB). The amplifier can be used on other frequencies such 1.8GHz for mobile communication and 2.2GHz for wireless and RF applications.

II. CLASSES OF POWER AMPLIFIER OPERATION

GaAsFET power amplifiers used in transceiver circuits exhibit varying degrees of nonlinearity, depending on its class of operation. The output current's harmonic content varies with the DC bias at the gate of the GaAsFET device,

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while maintaining a constant RF input signal. In certain applications, it may be desirable to have the transistor conducting for only a certain portion of the input signal. The portion of the input RF signal for which there is an output current determines the class of operation of a power amplifier. Discusses four classes of power amplifier operation, which are predominantly used in Doherty power amplifiers. Figure (1) shows the typical classes based on the

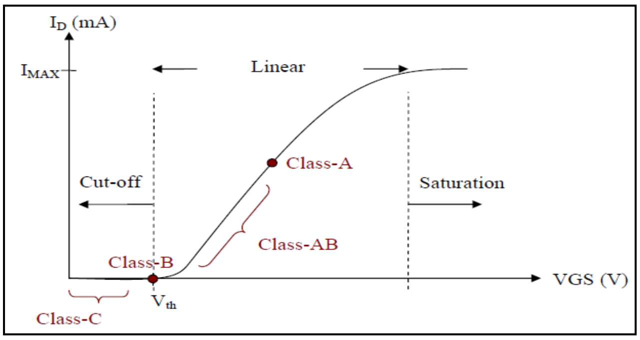

Fig (1): Classes of operation of Power amplifier based on transfer characteristics

transistor transfer characteristics [6].

III. THE THREE-WAY DOHERTY AMPLIFIER

In a classical Doherty amplifier operation high efficiency is obtained over a range of 6dB below maximum output power. The concept of multi-way Doherty amplifier is used to maintain the efficiency in the back-off region that can be extended beyond the classical design. The output impedances of the amplifier cells should be chosen to satisfy the output power relations between the carrier and peaking cells [1]. However, it should draw attention to the fact that too high or too low characteristic impedances of transmission lines in the output combining circuit are unpractical for realization. The configuration of a 3-way Doherty circuit consists of three amplifiers, namely the "carrier" and the "peaking1, peaking2" as shown in figure (2). The amplifiers are connected in parallel with their outputs joined by a quarter-wave transmission line, which performs impedance transformation. The peaking amplifiers delivers current as the carrier amplifier saturates, thereby reducing the impedance seen at the output of the carrier amplifier. Thus, the carrier amplifier delivers more current to the load while it is saturated because of the "load-pulling" effect. Since the carrier amplifier remains closer to saturation for a range of 6 dB backed off from the maximum input power, the total efficiency of the system remains high over that range.

The characteristic impedances of the quarter-wave transformers in output combiningnetwork of the three-way Doherty power amplifier were found to be R_1=50 Ohm, R_2=16.667 Ohm, while the quarter-wave transformer with characteristic impedance R_t=35.35 Ohm transforms.

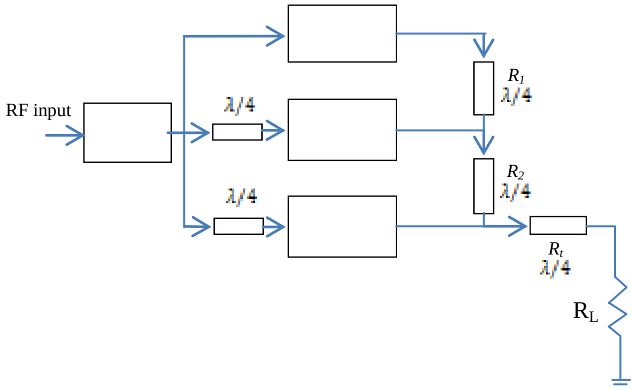

Fig (2): Block Diagram of three-way DPA

IV. ACTIVE LOAD PULL TECHNIQUE

The active load pull technique is based on the principle that applying current from a second phase coherent source can vary the resistance or reactance of a RF load. This defies the usual understanding that RF loads are physically passive entities. The following analysis explains the concept as presented [7]. According to circuit theory, generator 1 sees a load resistance of R when generators (2 and 3) are set to supply zero current as shown in figure(3). If generators (2 and 3) starts to supply current as well as generator 1, the voltage appearing across the load resistor can be given as.

$$V_L = R_L[I_1 + (I_2 + I_3)] \quad (1)$$

With the addition of supply current to the load resistance from second generator, the resistance seen by generator 1 now becomes.

$$R_1 = R_L\left[\frac{I_1+(I_2+I_3)}{I_1}\right] (2)$$

Likewise, the resistance seen by generator 2 can be represented as.

$$R_2 = R_L\left[\frac{I_1+(I_2+I_3)}{I_2}\right] (3)$$

The resistance seen by generator 3 can be represented as.

$$R_t = R_L\left[\frac{I_1+(I_2+I_3)}{(I_2+I_3)}\right] (4)$$

The above concept can be extended to ac circuits by using complex notation for representing the magnitude and the phase of the currents and voltages and the resistive and reactive components. Thus, equation(4)can be represented as.

$$Z_1 = R_L\left(1 + \frac{I_1}{(I_2+I_3)}\right) (5)$$

Z_1 can be transformed to higher value if I_t is made in phase with I_1 and to a smaller value if I_t is made anti-phase with I_1.The concept of load pull technique can be implemented with transistors if the generators are replaced by the

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outputtrans-conductance of the RF transistors. Thus, when three transistors are connected in parallel, one can modify the impedance seen by the other through proper biasing. This concept, extended to the combination of three unlike devices with different periphery and biasing, results in the three-way Doherty configuration [7].

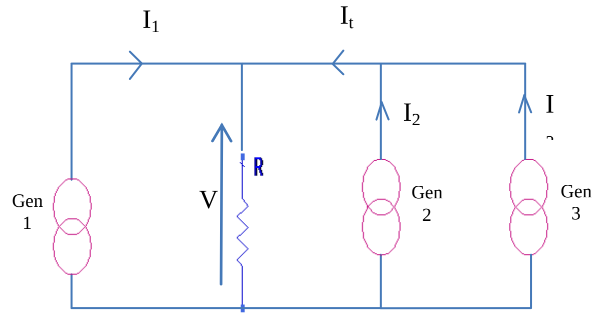

Fig (3): Active Load Pull schematic

V. DESIGN OF THREE-WAY DOHERTY POWER AMPLIFIER

Load pull is a technique wherein the load impedance seen by the device under test (DUT) is varied and the performance of the DUT is simultaneously measured [8]. Similarly in source pull the performance of the DUT for varying source impedances is measured. The measured results are very useful in determining the optimum load and source impedance which the device must see to give the best performance. Load pull, in particular, is commonly used to determine the load impedance required for maximizing efficiency. The input of a power amplifier is usually conjugate matched and the source pull is not always required. It should be noted that the calculated impedance values vary with bias. In this design load pull and source pull were performed to obtain maximum efficiency. The results obtained from these simulations show that the optimum value of load impedance is equal to (5.323+j*3.586)Ohm, and source impedance is equal to (2.19+j*6.25) Ohm as shown in figure(4) and figure(5) respectively. impedance and the input transmission line $\lambda/4$ equal to 50 Ohm.

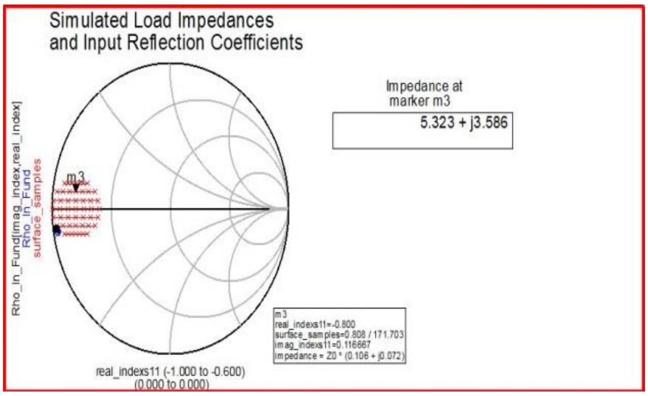

Fig (4): Load Pull Analysis to determine load impedance for maximum efficiency

The input matching network, input source The value of power supply Vlow is equal to -2.4V for biasing of the carrier amplifier, $Vlow_{1,2}$ is equal to -3.8V for biasing of the peaking amplifiers (peaking 1 amplifier and peaking 2 amplifier) and drain voltage of the carrier and peaking amplifiers Vhigh is 4.8V.

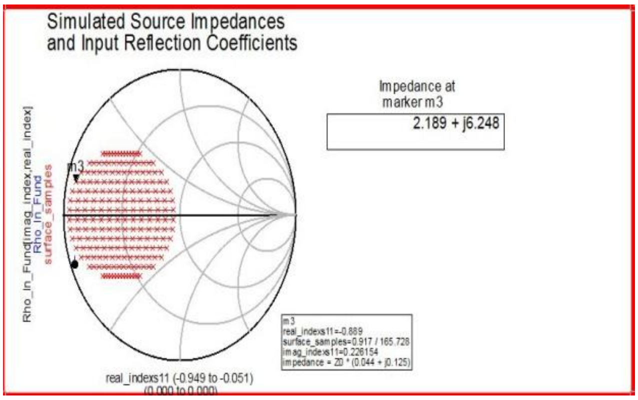

Fig (5): Source Pull Analysis to determine input impedance for maximum efficiency

VI. SIMULATION RESULTS

The three-way DPA has been designed in this work by using ADS software for base-station applications such as W-CDMA and 3G system. Doherty amplifier is a combination of Class AB carrier stage and Class C peaking stages (peaking 1, peaking 2). One tone simulations were performed with a center frequency of 2.14GHz. Various procedures involved in the design of the 3-Way DPA amplifier such as DC simulation, bias point selection, source-pull and load-pull characterization, input and output matching circuit design and the design of suitable harmonic traps are explained.One-tone harmonic balance simulations were performed on the DPA design. Harmonic balance is a frequency-domain analysis technique for simulating distortion in nonlinear circuits. Harmonic balance determines the spectral content of voltages and currents in the circuit. It is very useful to compute intercept point and intermodulation distortion. This is also used to determine PAE of the amplifier in the presence of interferers. Figure (6) explains the final realization of three-way DPA design on the one tone simulation. The amplifier has very good PAE% is equal to (70.15%) at 1dB maximum output power (34.06dBm) as show in figure (7). Furthermore the amplifier has high linearity and low distortion via through, see the output spectrum at fundamental frequency on figure (8). The minimum value of amplitude and phase distortion have been obtained in this design is shown in figure (9).Figure (10) represents the results of the input and output matching of the three-way DPA design via through input, output reflection coefficients, gain of the PA and feedback power transformer (S_{11}),(S_{22}),(S_{21}) and (S_{12}) respectively. Figure(11) shows a power sweep with output power, PAE, and gain as a function of input power. The characteristic behavior of the 3-Way DPA is apparent from the fact that the PAE reaches an initial peak and remains high until peak power is reached.

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This initial peak in PAE at (74.334%) occurs at an output power of(35dBm).The P_{1dB} is at $P_{in,1dB}$ (27.5dBm) and $P_{out,1dB}$ (34.06dBm).

The gain is increasing with increasing input power to give maximum gain which is equal to (7.866dB) at input power (22.5dBm), and with output power equal to (30.366dBm). After this peak value, the gain starts decreasing with increasing input power. The output spectrum harmonic with input power is shown in figure(12). It is clear that the 3rd harmonic is increasing with increasing of input power. The value of 3rd harmonic was reduced by amount of (-20dBm) at (25dBm) input power and starts increasing after that value. The overall difference between the 1st harmonic and the 3rd one is about 40dBm or more which gives the amplifier good output spectrum characteristics. Figure (13) shows the output power with input power at variable input frequency (1800, 2000, 2140 and 2200)MHz. It's clear that the maximum output power, PAE and gain can be obtained at input frequency equal to 2.14GHz, and at input signal frequency equal to 2GHz and 2.2GHz. The amplifier still has good output power, PAE and gain. Decreasing the frequency to 1.8GHz will reduce the gain of the amplifier to a very small value especially at small values of input power. But at higher value of input power, greater than 20dBm, the three-way Doherty amplifier can be used for W-CDMA, cdma2000 and 3G base-station (2.14GHz) and (2.2GHz).

Also, in this work, the three-way DPA, two-way DPA (classical DPA) and conventional power amplifier type class AB have been designed by using ADS software. The results show that three-way DPA has very good power added efficiency, gain and output power at different back-off regions below maximum output power compared with conventional power amplifier and classical Doherty power amplifier. At 1dB compression point of the output power, the PAE% is equal to 70.134% at $P_{out,1dB}$ of 30.06dBm for three-way DPA when input power is equal to 27.5dBm. in the two-way DPA, the PAE is equal to 59% at $P_{out,1dB}$ of 33.625dBm when input power is 27dBm. Also in the Class AB power amplifier, the PAE is equal to 51% at $P_{out,1dB}$ equal to 29.132dBm for input power is 21dBm as shown in figure (14). Figure (15) represents that three-way Doherty power amplifier has very high efficiency and linearity

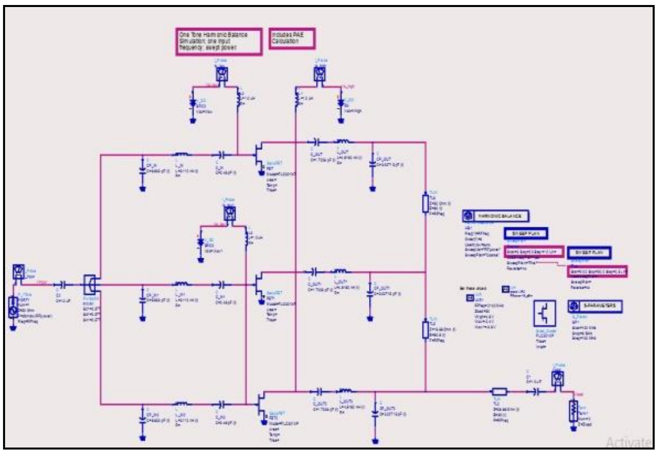

Fig (6): Schematic of the three-way Doherty power amplifier design

compared with class AB power amplifier and two-way

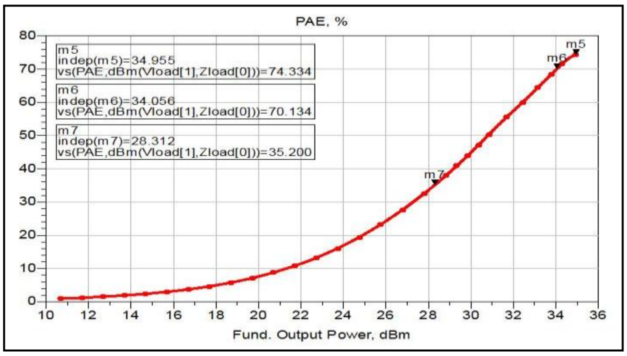

Fig (7): Power Added Efficiency (PAE%) of the 3-Way DPA design at $P_{out,max}$(m5),$P_{out,1dB}$(m6) and $P_{out,6dB}$ (m7)

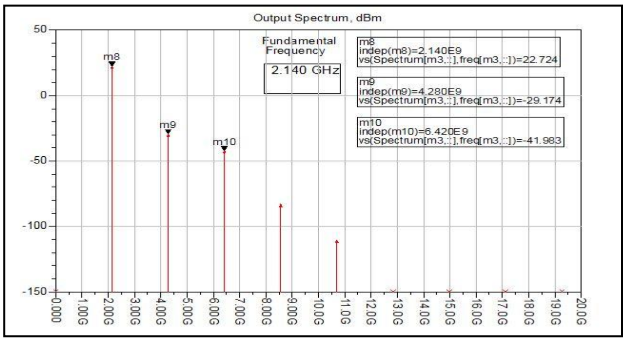

Fig (8): Output spectrum of the three-way DPA

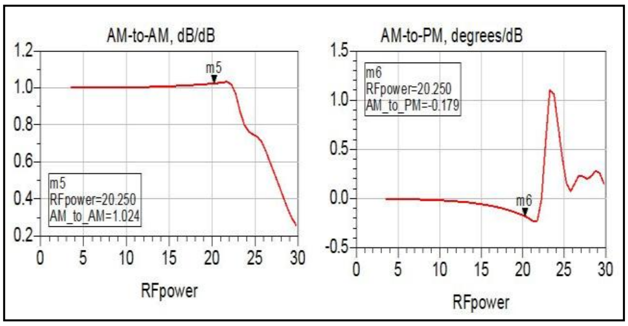

Fig (9): Amplitude distortion and Phase distortion

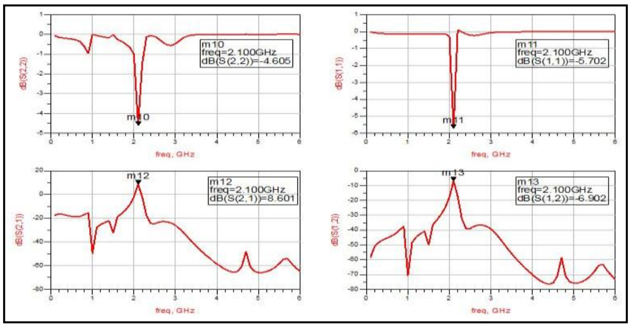

Fig (10): Results of the input and output matching of the three-way DPA design

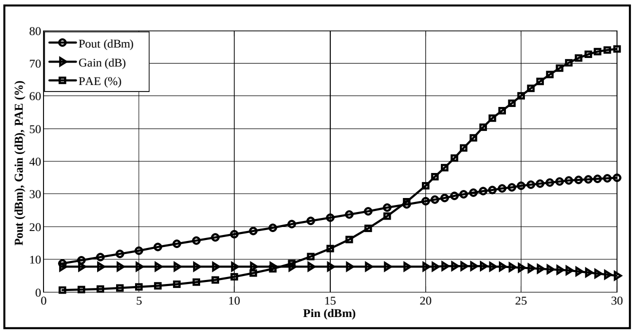

Fig (11): Output power, gain, and PAE as a function of input power

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Doherty power amplifier.

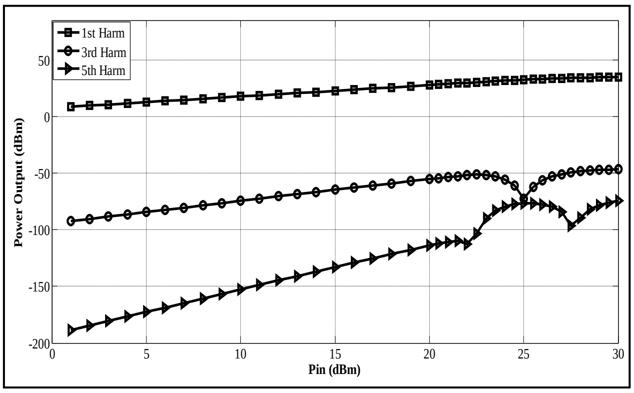

Fig (12): Power harmonics with input power

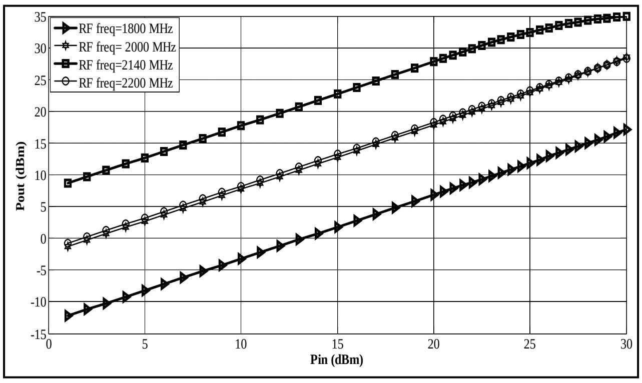

Fig (13): Output power as a function of input power for difference input signal frequencies

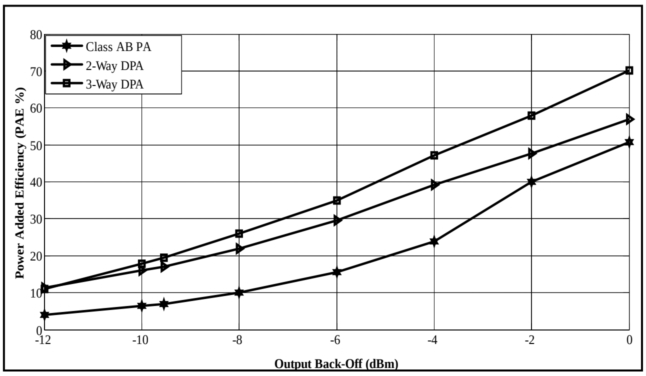

Fig (14): PAE of the conventional PAs and N-Way DPA with different output back-off points for W-CDMA base-station

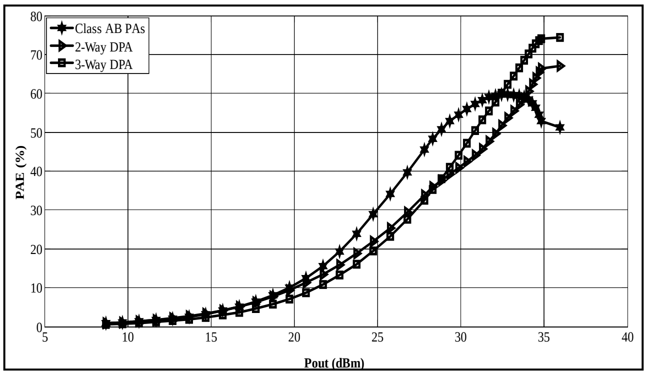

Fig (15): PAE of the conventional PAs and N-Way DPA with output power for W-CDMA base-station

VII. CONCLUSION

The analysis and design of three-way Doherty power amplifier were studied at different operating frequency. It is found that the amplifier can operate at W-CDMA base station and 3G mobile system at input power level more than 20dBm. The amplifier has good output spectrum and the 3rd harmonic spectrum is less than the main spectrum by amount of 40dBm or more. The amplifier has very good power added efficiency, gain and output power at output back-off regions below maximum output power compared with conventional power amplifier (Class AB) and classical DPA (Two-way DPA). The third order intermodulation (IDM3) has been obtained about (-54.45dBc) at maximum output power (34.06dBm) and input power (20.25dBm). The amplitude distortion is gotten about (1.023 dB/dB), and phase distortion about (-0.179 degree/dB).

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