Analysis on the Balanced Class-E Power Amplifier for the Load Mismatch Condition★

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Abstract. Analysis and simulation are presented of the mismatched load condition for a balanced class-E power amplifier, which is based on 90° hybrids at its input and output. The performances of the 200-Watt balanced class-E amplifier, such as the output power and efficiency, were analyzed and compared to the conventional single-ended class-E power amplifier for the 1:3 VSWR mismatch condition. The simulated results showed that the balanced class-E power amplifier has a standard deviation of 0.7 dB at an average output power of 51 dBm for complete 1:3 VSWR deviation, while the single-ended amplifier has a standard deviation of 2.4 dB at the same output power. For power-added efficiency, the balanced amplifier has a much lower standard deviation of 1.9 % compared to the single-ended amplifier which has 10.9 % at the same condition.

Keywords: Class-E amplifier, load mismatch, balanced power amplifier.

1 Introduction

Transmitters for wireless communications or wireless power transmission systems require very high energy efficiency and stable operation. Power amplifiers, as one of the most critical components in the performance of a transmitter, should have very high efficiency and environmentally insensitive operation. Since its output port is connected to an antenna or resonator, it could have no fixed load condition [1], [2].

General power amplifiers are designed to have a load of 50 Ω at which they can deliver the optimum output characteristics. If they are exposed to any mismatched condition, their performances can be seriously degraded or even damaged. To reduce

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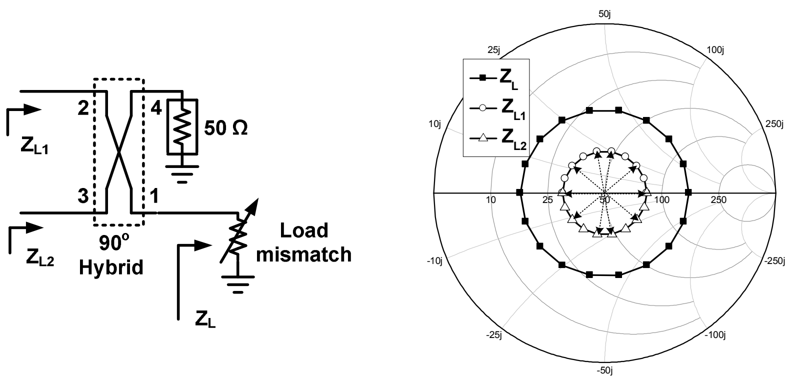
its performance sensitivity to the mismatched condition, an isolator can be used between the power amplifier and the antenna. However, the isolator is expensive, requires space, and is not lossless. In some applications, it is often very difficult to find appropriate isolators which are suited for the required frequency band or the required power level [3], [4].

An alternative way to improve the insensitivity to load mismatch conditions is to adopt a 90° balanced configuration [3]-[7]. The balanced amplifier has two amplifiers in parallel. One amplifier has opposite impedance from 50 Ω to the other when the mismatch condition happens. The opposite way for the output performances due to the opposite impedances from 50 Ω for the two parallel amplifiers makes compromise for the overall output performances [8], [9].

In this paper, we applied the 90° balanced structure to a high-efficiency class-E power amplifier. Analysis and simulation for the balanced class-E amplifier were carried out for the mismatched load condition. The results were also compared to the single-ended class-E amplifier, which has the same output power. For the comparative analysis, both 200-Watt balanced and single-ended class-E amplifiers were designed at the 6.78 MHz band. A given condition of the 1:3 voltage standing wave ratio (VSWR) mismatch was used for this comparative study.

2 Load mismatch condition for the balanced power amplifier



(a) (b)

Fig. 1. (a) load network with a 90° hybrid coupler, (b) impedances for the mismatch condition for a VSWR of 1:3.

A balanced amplifier with 90° hybrids has more stable operation for the input or output mismatch condition because the reflected signal due to the mismatch can be absorbed in the hybrid's isolation port [7]. Fig. 1(a) shows a typical load network for the balanced amplifier. When the load impedance of Z_L is in a mismatched condition, two internal amplifiers see little changed load impedances of Z_{L1} and Z_{L2}, respectively.

Reflection coefficients of each internal amplifier can be easily written as functions of a reflection coefficient of the load [9].

$$\Gamma_{L1} = -\frac{\Gamma_L}{2} \quad , \tag{1}$$

$$\Gamma_{L2} = \frac{\Gamma_L}{2} \quad . \tag{2}$$

Based on (1) and (2), the reflection coefficients of each parallel amplifier are plotted on a Smith chart, as shown in Fig. 1(b), for the case that the balanced amplifier has a 1:3 VSWR mismatch. As can be seen from the equations and figure, the internal amplifiers suffer from smaller mismatch reduced by half compared to that of the overall amplifier. This is the first benefit of the balanced amplifier.

The normalized impedance can be expressed using a lower case letter. Because the normalized load impedance z_{L1} is a function of its reflection coefficient of Γ_{L1}, a relationship between z_{L1} and z_L can be derived as:

$$z_{L1} = \frac{z_L + 3}{3z_L + 1} \quad . \tag{3}$$

Likewise, the relationship between z_{L2} and z_L can also be given as:

$$z_{L2} = \frac{3z_L + 1}{z_L + 3} \quad . \tag{4}$$

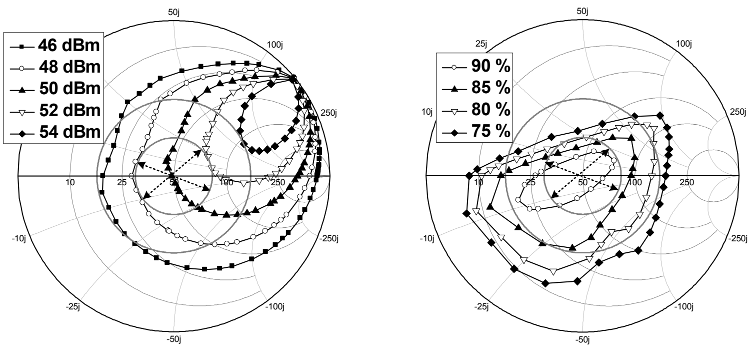
From (3) and (4), we can derive the relationship between the two normalized impedances as:

$$z_{L1} = \frac{1}{z_{L2}} \quad . \tag{5}$$

The normalized impedances of two parallel amplifiers are exactly reverse proportional to each other. This means that if the impedance of one amplifier increases due to the load mismatch, then the impedance of the other amplifier decreases from the optimum value. In Fig. 1(b), z_{L1} and z_{L2} from the same mismatch condition are located at exactly opposite positions from the center of the Smith chart. This is the second and main benefit of the balanced amplifier for the load mismatch condition.

Fig. 2 shows load-pull simulation results for the single-ended class-E amplifier which is optimized for high efficiency with an output of more than 100 Watts. The details of the amplifier design will be presented in the next section. At its optimum point, i.e. no mismatch, the amplifier has an efficiency of 92.2 % at an output power of 50.1 dBm.

For the given mismatch condition of a VSWR of 1:3, the output power changes from about 46 to 54 dBm along the outer circle shown in the charts (see Fig. 2(a)). The efficiency also drops much lower than 75 % (see Fig. 2(b)). For the same mismatch on the balanced power amplifier, a smaller VSWR circle can be observed



(a) (b)

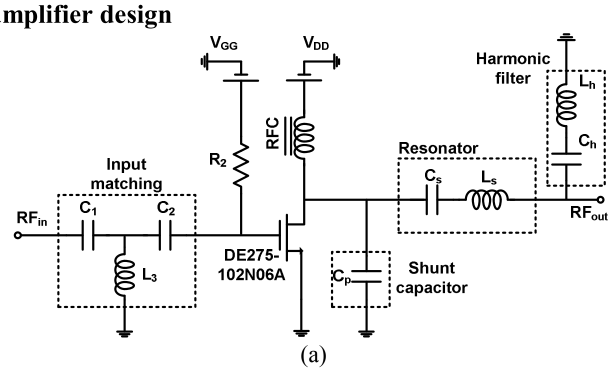
Fig. 2. Load-pull simulation results for the single-ended class-E amplifier: (a) output power, (b) efficiency.

on the charts for each internal amplifier, as well as two different impedances that are at the opposite positions from the center. As a result, one amplifier can have higher output power, while the other has a lower output power than that of the amplifier without mismatch. The efficiency drop can be much smaller because of the smaller VSWR circle.

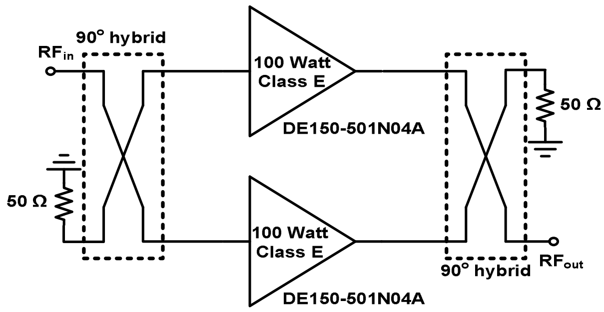
For example, if Z_L becomes 19-j15.9 Ω, Z_{L1} and Z_{L2} are 68.7+j23.2 and 32.7-j11 Ω, respectively. For this case, the power amplifier with an impedance of Z_{L1} has an output power of 51.9 dBm and an efficiency of 89.1 %. Another power amplifier with an impedance of Z_{L2} has an output power of 48.1 dBm and an efficiency of 91.1 %. We can intuitively see that the balanced amplifier will have average performances of both amplifiers. However, the single-ended amplifier with an impedance of just Z_L has an output power of 45.8 dBm and an efficiency of 86 %, which are significantly worse than the expected performances of the balanced amplifier for the same mismatch.

3 Comparison between single-ended and balanced class-E power amplifier

3.1 Power amplifier design



(a)



(b)
Fig. 3. Schematic diagrams: (a) single-ended class-E power amplifier, (b) balanced amplifier configuration.

The class-E amplifier has very simple structure and an ideal efficiency of 100 % [10], [11]. Its load network has a parallel capacitor and a series L-C resonant circuit. It also has an additional harmonic filter to remove leakages of the 2nd and 3rd harmonics. To verify the characteristics of the balanced power amplifier, a 200-Watt single-ended class-E amplifier and a 200-Watt balanced class-E amplifier were designed. Their schematic diagrams are shown in Fig. 3. The balanced amplifier is based on two 100-Watt single-ended class-E amplifiers and two hybrids at the input and output. The 200-Watt and 100-Watt amplifiers were designed using IXYS's DE275-102N06A and DE150-501N04A, respectively. Both devices have high break-down voltages of more than 500 V.

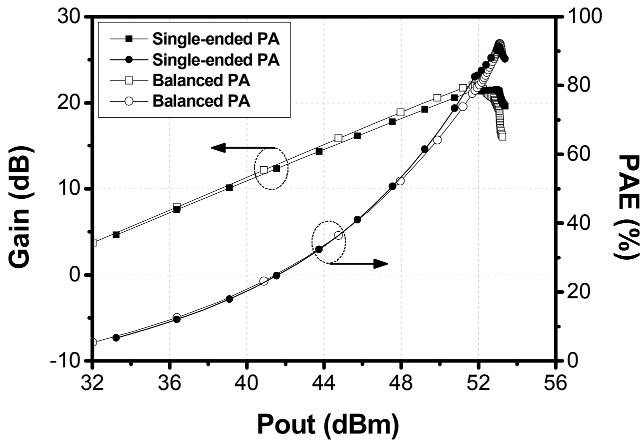
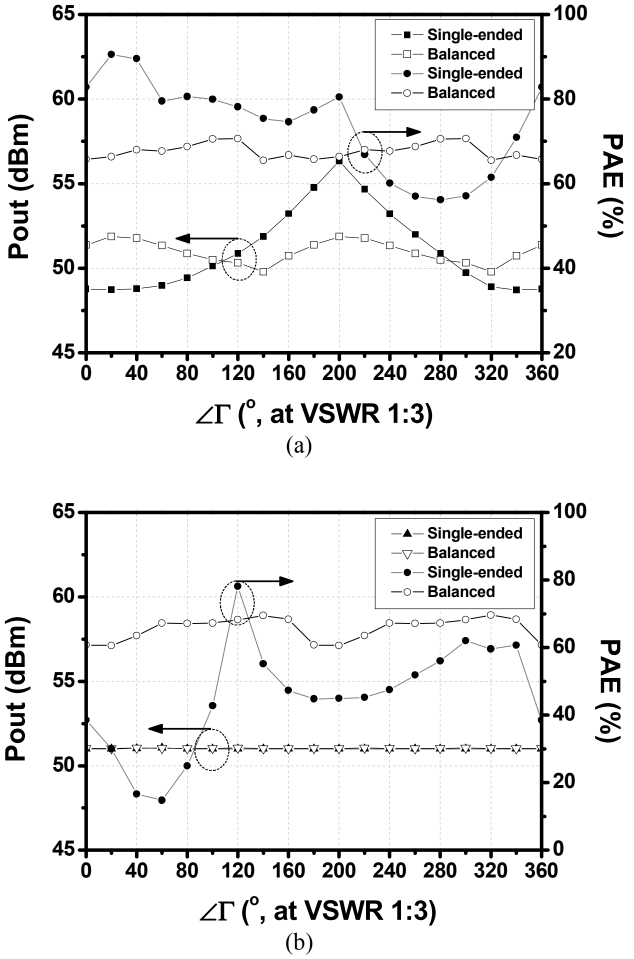


Fig. 4. Simulated results: gain and PAE.

The gain and power-added efficiency (PAE) performances of the single-ended and balanced power amplifiers at the optimum load condition are shown in Fig. 4. The single-ended PA with a drain bias of 210 V exhibits a gain of 21.3 dB and a PAE of 91.3 % at an output power of 53.1 dBm. The balanced PA with a drain bias of 105 V has a gain of 18.5 dB and a PAE of 92.2 % at the same output power of 53.1 dBm.

3.2 Comparison under the mismatch condition



(b)

Fig. 5. Simulated output power and PAE of the single-ended and balanced class-E amplifiers under the load mismatch condition of 1:3 VSWR: (a) fixed input power to have an output power of 53 dBm at the 50 Ω load, (b) fixed output power of 51 dBm.

Fig. 5(a) represents the simulated output power and efficiency results according to the total 360° phases of the reflection coefficient for the load mismatch of VSWR 1:3. For the fixed input power where both single-ended and balanced power amplifiers have about 200 Watts at the 50 Ω load, the single-ended class-E amplifier had an average output power of 51 dBm with a standard deviation of 2.4 dB and an average efficiency of 73.8 % with a standard deviation of 10.9 %. On the other hand, the balanced class-E amplifier exhibited an average output power of 51 dBm with a standard deviation of just 0.7 dB and an average efficiency of 67.7 % with a standard deviation of as low as 1.9 %.

Fig. 5(b) shows the simulated output power and efficiency with the same conditions, except that both amplifiers have variable input power level set to have a fixed output power of 51 dBm. The balanced class-E amplifier exhibited an average efficiency of 65.6 % with a low standard deviation of 3.4 %, while the single-ended counterpart had an average efficiency of 45.2 % with a standard deviation of 15.9 %. An overall summary of the comparative simulations is presented in Table I.

Table I Performance comparison under the load mismatch condition

	Input power (dBm)	Output Power (dBm)	Efficiency (%)
Single-ended	31.7 (fixed)	48.7 ~ 56.3 51 (average) 2.4 (standard deviation)	56.2 ~ 90.5 73.8 (average) 10.9 (standard deviation)
Balanced	34.6 (fixed)	49.8 ~ 51.9 51 (average) 0.7 (standard deviation)	65.5 ~ 70.6 67.7 (average) 1.9 (standard deviation)
Single-ended	29.9 ~ 46.5	51 (fixed)	14.8 ~ 78.2 45.2 (average) 15.9 (standard deviation)
Balanced	30 ~ 37.5	51 (fixed)	60.6 ~ 69.6 65.6 (average) 3.4 (standard deviation)

4 Conclusions

The output performances of the single-ended and balanced class-E power amplifiers in the load mismatch condition were analyzed and compared. The insensitive nature of the balanced power amplifier to load mismatch was investigated under two different conditions: a fixed input power and a fixed output power with a tunable input.

To verify our analysis, a 200-Watt high-power single-ended power amplifier and a balanced class-E power amplifier were designed for the 6.78 MHz band. The simulated results prove that the balanced class-E power amplifier has significantly superior insensitivity for its output power and efficiency characteristics over the given mismatch condition of VSWR 1:3. It has a much lower standard deviation of 3.4 % in its efficiency for the fixed output power of 51 dBm, while the single-ended class-E amplifier has 15.9 % for the same condition. Therefore, the balanced power amplifier can be more suitable for some applications with high environmental variation, such as wireless power transferring systems.

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