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Steady-State Behavior of Class-E Amplifier Outside Nominal Operation Taking into Account MOSFET-Body-Diode Effect

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Abstract

We present steady-state analysis for the class-E power amplifier outside the class-E zero-voltage switching and zero-derivative switching (ZVS/ZDS) conditions. The analytical expressions in this paper include the MOSFET-body-diode effect. By carrying out circuit experiments, it is shown that the analytical predictions agreed with the experimental results quantitatively, which indicates the validity of the analytical expressions.

1. Introduction

The class-E amplifier[1]-[7] can achieve high power conversion efficiency at high frequencies because of the class-E zero-voltage switching and zero-derivative switching (ZVS/ZDS) conditions. Therefore, most papers on the class-E amplifier concern the class-E amplifier under the class-E ZVS/ZDS conditions, which are called “nominal conditions”. However, the implemented circuits always have some variations, for example, in element values, operating frequency and switch off duty ratio. We recognize it is quite important to comprehend the operation of class-E amplifiers outside nominal conditions with the MOSFET-body-diode effect. The designer understands the characteristics of the operation intuitively from analytical expressions.

We present a steady-state analysis for the class-E amplifier outside the class-E ZVS/ZDS conditions and with highly loaded quality factor and any duty ratio, taking into account the MOSFET body diode. The analytical expressions describe three switching patterns. With the MOSFET-body-diode effect taken into consideration, the applicable parameter range of the analytical expressions in this paper is much wider than that of the previous analytical expressions. The results of circuit experiments show that the analytical predictions agreed with the experimental results quantitatively, which validates the analytical expression accuracy.

2. Circuit Description and Principle Operation

Figure 1(a) shows the circuit topology of the class-E power amplifier [1]-[7]. This amplifier is composed of a dc-supply voltage source \( V_{DD} \), a dc-feed inductance \( L_c \), MOSFET as the switching device \( S \), a shunt capacitance \( C_s \), and a series-resonant filter \( L_0-C_0-R \). The class-E amplifier achieves high power-conversion efficiency at high frequencies when the class-E amplifier satisfies the class-E ZVS/ZDS conditions. These conditions are expressed as

\[
\psi_s(2\pi D) = 0, \quad \left. \frac{d\psi_s}{d\theta} \right|_{\theta=2\pi D} = 0
\]

where \( \psi_s \) is the voltage across the switch \( S \). Figure 2 depicts example waveforms in the class-E power amplifier under nominal operation. In the class-E power amplifier, the switch \( S \) is driven by an input signal \( \psi_s \). During the switch-off interval, the current through the shunt capacitance produces
Figure 2: Example waveforms in the class-E power amplifier satisfying nominal conditions for \( D = 0.5 \)

Figure 3: Switching patterns of the class-E amplifier: (a) Case 1, (b) Case 2, (c) Case 3

the switch voltage \( v_s \). Since the resonant filter has a high quality factor \( Q \), the output current \( i_o \) is sinusoidal. In addition, the output filter produces a phase shift \( \phi \) between the input signal and the output current, as shown in Figure 2.

3. Waveform Equations Outside Nominal Conditions

The analytical steady-state waveform equations for the class-E amplifier outside nominal conditions are given following the analysis process presented in [4].

3.1 Switching patterns

Figure 3 shows the switching patterns of the class-E amplifiers considered in this paper. We classify the switching patterns into three cases, as shown in Figure 3. Figure 3(a) shows the switch waveform, which does not reach zero during the switch-off interval. This switching pattern is called “Case 1” in this paper. In this case, turn-on switching loss occurs at the turn-on instant. When the switch voltage reaches zero prior to the turn-on switching instant, the MOSFET antiparallel body diode turns on, as shown Figure 3(b); this is “Case 2”. In Case 2, ZVS is achieved at \( \theta = \theta_1 \) because of the use of the MOSFET body diode, where \( \theta = \omega t \) represents the angular time. The on-resistance of the body diode is, however, much larger than the on-resistance of the MOSFET. Therefore, the large conduction loss occurs in this case. There is also a case in which the switch voltage returns to positive at \( \theta = \theta_2 \) via the MOSFET-body-diode on-state, as shown in Figure 3(c), which is “Case 3”. In this case, both the turn-on switching loss and the conduction loss on the MOSFET body diode occur.

In the previous research papers, the steady-state waveform equations in [4] expresses only Case 1. The steady-state waveforms presented in [5] and [6] are valid for Cases 1 and 2. There are no analytical steady-state waveform equations that are valid for Cases 1, 2, and 3.

3.2 Assumptions and parameters

Figure 1(a) shows the circuit topology of the class-E amplifier. First, the following parameters are defined.

1. \( A = f_0 / f = \omega_0 / \omega = 1 / \sqrt{L_0 C_0} \): The ratio of the resonant frequency to the operating frequency.
2. \( B = C_0 / C_S \): The ratio of the resonant capacitance to the shunt capacitance.
3. \( D \): The switch-off duty ratio of the switch \( S \).
4. \( Q = f_0 L_0 / R \): The loaded Q-factor.

The circuit analysis for deriving the waveform equations are based on the following assumptions.

(a) The MOSFET works as an ideal switching device, namely, it has zero on-resistance, infinite off-resistance and zero switching times.
(b) The dc-feed inductance \( L_C \) is large enough that the current through the dc-feed inductor is constant.
(c) The loaded Q-factor is high enough to generate a sinusoidal output current \( i_o \).
(d) The resonant inductor \( L_0 \) is divided into \( L_r \) and \( L_s \), where \( L_r = 1 / \omega_0^2 C_0 \).
(e) All the passive elements are linear and have zero equivalent series resistances (ESRs).
(f) The circuit operations are considered in the interval \( 0 \leq \theta \leq 2\pi \). The switch is in the off-state for \( 0 \leq \theta < 2\pi D \) and in the on-state for \( 2\pi D \leq \theta < 2\pi \).

By the above assumptions, the equivalent circuit shown in Figure 1(b) is obtained.
3.3 Waveform equations

From assumption (c), the output current is

$$i_o = I_m \sin(\theta + \phi)$$

(2)

In Eq. (2), $i_o$ is the amplitude of the output current and $\phi$ is the phase shift between the input signal and the output current. Additionally, the switch voltage is given by

$$v_S = \begin{cases} 
    v_{S1} = A_2 B_2 Q [I_{DD} \theta + I_m [\cos(\theta + \phi) - \cos \phi]], & \text{for } 0 \leq \theta < \theta_1 \\
    v_{S2} = V_D, & \text{for } \theta_1 \leq \theta < \theta_2 \\
    v_{S3} = A_2 B_2 Q [I_{DD} (\theta - \theta_2)] \\
    + I_m [\cos(\theta + \phi) - \cos(\theta_2 + \phi)], & \text{for } \theta_2 \leq \theta < 2\pi D \\
    v_{S4} = 0, & \text{for } 2\pi D \leq \theta < 2\pi
\end{cases}$$

(3)

where $V_D$ is the forward voltage drop of the MOSFET body diode and $I_{DD}$ is the dc-supply current.

Because of assumption (b), the dc voltage drop across the choke inductor $L_C$ is zero. Therefore, the dc-supply voltage is

$$V_{DD} = \frac{1}{2\pi D} \int_0^{2\pi D} v_S d\theta$$

(4)

From assumption (d), $I_0$ is divided into $I_r$ and $I_r$, where $I_r = C_0\omega_0^2$, as shown in Figure 1(b). Therefore, the impedance of the resonant circuit $C_0L_r$ is zero at the operating frequency. By applying Fourier analyses, the voltage amplitudes on $R$ and $L_r$ are

$$R I_m = \frac{1}{\pi D} \int_0^{2\pi D} v_S \sin(\theta + \phi) d\theta$$

(5)

and

$$L_r I_m = \frac{1}{\pi D} \int_0^{2\pi D} v_S \cos(\theta + \phi) d\theta$$

(6)

From Eqs. (4), (5), and (6), $I_m$, $\phi$, and $I_{DD}$ can be derived analytically. The current through the switch is

$$i_S = \begin{cases} 
    0, & \text{for } 0 \leq \theta < \theta_1 \\
    I_{DD} - I_m \sin(\theta + \phi), & \text{for } \theta_1 \leq \theta < \theta_2 \\
    0, & \text{for } \theta_2 \leq \theta < 2\pi D \\
    I_{DD} - I_m \sin(\theta + \phi), & \text{for } 2\pi D \leq \theta < 2\pi
\end{cases}$$

(7)

When substituting $\theta_1 = \theta_2 = 0$ into $v_S$, we can obtain the same equations as given in [3]. Therefore, when the switch voltage is as in the Case 1, $\theta_1$ and $\theta_2$ are given as $\theta_1 = \theta_2 = 0$, as shown in Figure 3(a). When the switch voltage is as in the Case 2 switching pattern, $\theta_2$ is renewed as $\theta_2 = 2\pi D$, as shown in Figure 3(b) and $\theta_1$ is obtained numerically by Newton’s method. When the switch voltage is as in the Case 3 switching pattern, $\theta_1$ and $\theta_2$ are obtained numerically by Newton’s method.

4. Experimental Verification

4.1 Nominal state

For validating the analytical expressions, circuit experiments were carried out. The design specifications for nominal operation were given as follows: operating frequency $f_{nom} = 1 MHz$, dc-supply voltage $V_{DD} = 5 V$, output resistor $R = 5 \Omega$, switch-off duty ratio $D = 0.5$, and loaded quality factor $Q = 10$ where the subscript “nom” means the parameter value under nominal conditions. First, we carry out the design of the class-E amplifier with the nominal conditions in Eq. (1) for $\theta_1 = \theta_2 = 0$ [7]. The design parameters are obtained as $L_C = 34.67 \mu H$, $I_0 = 7.96 \mu H$, $C_T = 5.84 \mu F$, and $C_0 = 3.60 \mu F$, which means $A = 0.94$ and $B = 0.62$, as given in Table 1. An IRF530 MOSFET device was used in the circuit experiment. Therefore, the forward voltage drop of the IRF530 MOSFET body diode is $V_D = 0.7 V$, determined using the Spice model of the IRF530 MOSFET. Table 1 gives the analytical predictions and experimental measurements for satisfying the class-E ZVS/ZDS conditions. Figure 4 shows the analytical and the experimental waveforms for the nominal conditions. It is seen from Fig. 4 that the class-E ZVS/ZDS conditions were achieved in this state. We define the state in Table 1 and Fig. 4 as the “nominal state”. At following measurements, some parameters varied from the nominal state.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Analytical</th>
<th>Measured</th>
<th>Difference</th>
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<td>$V_{DD}$</td>
<td>5.0 V</td>
<td>5.0 V</td>
<td>0.00 %</td>
</tr>
<tr>
<td>$D$</td>
<td>0.5</td>
<td>0.5</td>
<td>0.00 %</td>
</tr>
<tr>
<td>$f_{nom}$</td>
<td>1 MHz</td>
<td>1 MHz</td>
<td>0.00 %</td>
</tr>
<tr>
<td>$R$</td>
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</tr>
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<td>$L_C$</td>
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<td>43.0 µH</td>
<td>24.1 %</td>
</tr>
<tr>
<td>$L_0$</td>
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<td>8.01 µH</td>
<td>0.68 %</td>
</tr>
<tr>
<td>$C_{S,nom}$</td>
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</tr>
<tr>
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<td>3.53 nF</td>
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<tr>
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</tr>
<tr>
<td>$B$</td>
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</tr>
<tr>
<td>$P_o$</td>
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<td>2.87 W</td>
<td>−0.35 %</td>
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<tr>
<td>$\eta$</td>
<td>92.2 %</td>
<td>91.8 %</td>
<td>−0.46 %</td>
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</table>

4.2 Output Power and Power Conversion Efficiency

Figures 5 and 6 show the output power and the power conversion efficiency of the class-E amplifier as a function of $f f_{nom}$ and $C_S/C_{S,nom}$, respectively, which are obtained by changing the parameters $f$ and $C_S$ from the nominal state. It is seen from Figs. 5 and 6, that the analytical predictions agreed with the experimental measurements.
the class-E amplifier outside the nominal conditions. The steady-state waveform equations include the MOSFET-body-diode effect. Waveforms, output power, and power-conversion efficiency obtained from the analytical expressions agreed with the experimental results quantitatively, which indicates the validity of the analytical expressions.

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References


