

Maximum Output Power of Class E Amplifier for a Given Transistor, Operating Frequency, and DC Supply Voltage

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Abstract: This paper analyzes maximum output power of class E amplifier with arbitrary transistor. It is important to estimate maximum output power of class E amplifier when a specification of transistor is given. In this paper, values of circuit parameters that gives maximum output power for given operating frequency, dc supply voltage, and output capacitance of the transistor are calculated. This paper presents scheme to calculate circuit parameters that maximum output power in this condition. Finally, some example calculations are shown when this scheme was applied to some actual power MOSFET transistors.

Keyword: Class E amplifier, Maximum output power, Transistor, Sub class E operation

1. Introduction

This paper presents an analytical result about maximum output electric power of a class E amplifier. When a transistor was specified, the highest switch voltage, the highest switch current and the lowest shunt capacitance are the restrictions in a design of a class E amplifier. These parameters can't be changed because they are predetermined transistor's specifications. On the other hand, linear parameters such as resonant element and load resistance are possible to be changed. Duty ratio is also possible to be changed and depends on a design of a drive circuit. The operating frequency and the dc supply voltage are unchangeable parameters because they are the external environments. In this paper, a procedure for obtaining circuit parameter, which achieves the maximum output power under above restriction is described. And results are verified in simulation using several actual transistors.

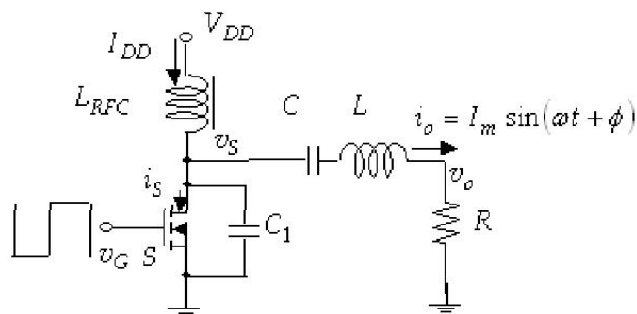


Fig. 1. Class E amplifier.

2. Amplifier with sub class E operation

Figure 1 indicates a circuit diagram of the class E amplifier analyzed in this paper. The class E amplifier consists of choke-coil L_{RFC} which supplies the electric power from direct current supply voltage source V_{DD} , shunt capacitor C_1 which are connected in parallel to the switching device S , the series resonant circuit $C-L$ which connects with load resistance R , and the load resistance R . Choke-coil L_{RFC} restricts an input electric current to direct current with the high inductance. A periodic voltage excitation is occurred to the switch voltage by the periodically operated switch and a sine wave electric current flows to load resistance. The output current is a sine wave current because a fundamental frequency component of the switch voltage is extracted by a series resonant circuit $C-L$, and only sinusoidal voltage of a switching frequency is output to load resistance.

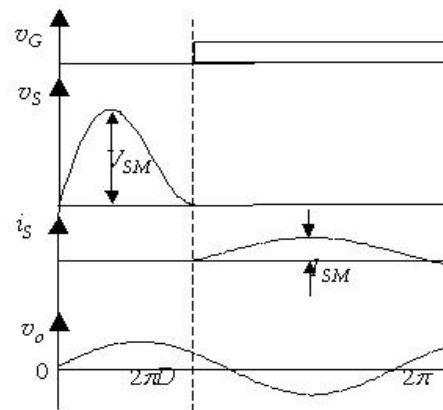


Fig. 2. Theoretical waveforms of class E amplifier.

Figure 2 indicates theoretical waveforms of the switch voltage and the output voltage. The switch is off from 0 of the phase to $2\pi D$, and it is on from $2\pi D$ to 2π of the phase. At the moment the switch turns on if the switch voltage becomes a zero, the power loss due to the switch turns on will become a zero. It is called the ZVS operation. At the moment the switch turns on if the inclination of the switch voltage waveform is a zero, it is called the ZDS operation. When the conditions of ZVS operation and ZDS operation are met at the same time, the highest efficient operation which is called the optimum class E operation, is achieved. When only ZVS operation is satisfied, switching loss becomes a zero. It's called the sub class E operation and is

said to be the operating condition by which the high efficiency is generally possible.

3. Output power when class E amplifier do sub class E operation

Output electric power P_o of the class E amplifier at the sub class E operation is obtained as follows [1].

$$P_o = \frac{I_m^2 R}{2} = \frac{2V_{DD}^2 \sin^2 \pi D \sin^2(\pi D + \phi)}{\pi^2 D^2 R} \quad (1)$$

where I_m is the output current amplitude and V_{DD} is the direct current supply voltage, and D is off duty ratio (the percentage of the off hour over the a period), and θ is an initial phase of the output current, and R is load resistance.

First, peak switch voltage $V_{SM}(=\max V_S)$ of the class E amplifier is expressed in a reference book [1] as the following formula.

$$V_{SM} = \frac{I_{DD}\theta_0 + I_m \cos(\theta_0 + \phi) - I_m \cos \phi}{\omega C_1} \quad (2)$$

where ω is the angular switching frequency, and C_1 is the shunt capacitance, output current I_m , input current I_{DD} , and phase θ_0 at the peak switch voltage. And they are expressed in the following formula.

$$I_m = \frac{2V_{DD} \sin \pi D \sin(\pi D + \phi)}{\pi DR} \quad (3)$$

$$I_{DD} = \frac{2V_{DD} \sin^2 \pi D \sin^2(\pi D + \phi)}{\pi^2 D^2 R} \quad (4)$$

$$\theta_0 = \begin{cases} -\phi + \sin^{-1} \left[\frac{\sin \pi D \sin(\pi D + \phi)}{\pi D} \right] & \text{for } I_m > 0 \\ -\pi - \phi - \sin^{-1} \left[\frac{\sin \pi D \sin(\pi D + \phi)}{\pi D} \right] & \text{for } I_m < 0 \end{cases} \quad (5)$$

When substituting the formula (3) and the formula (4) for the formula (2) and using the following formula (6), it's possible to show the peak switch voltage like the formula (7).

$$\omega C_1 R = \frac{\sin \pi D (-\pi D \cos \pi D + \sin \pi D) \sin 2(\pi D + \phi)}{\pi^2 D} \quad (6)$$

$$V_{SM} = \frac{V_{DD} [\sin(\pi D + \phi) + \sin \pi D] \theta_0 + \pi D [\cos(\theta_0 + \phi) - \cos \phi]}{D(\sin \pi D - \pi D \cos \pi D) \cos(\pi D + \phi)} \quad (7)$$

Highest switch electric current $I_{SM}(=\max I_S)$ is expressed in the following formula.

$$I_{SM} = \begin{cases} I_{DD} - I_m & \text{for } \phi < -\frac{\pi}{2} \cap \phi \leq \pi(0.5 - 2D) \\ I_{DD} - I_m \sin(2\pi D + \phi) & \text{for } \phi < -\frac{\pi}{2} \cap \pi(0.5 - 2D) < \phi \leq -\pi D \\ I_{DD} - I_m \sin \phi & \text{for } \phi < -\frac{\pi}{2} \cap -\pi D < \phi \\ I_{DD} - I_m & \text{for } -\frac{\pi}{2} \leq \phi \cap \phi \leq -\pi D \\ I_{DD} + I_m & \text{for } -\frac{\pi}{2} \leq \phi \cap -\pi D < \phi. \end{cases} \quad (8)$$

It's found that the maximum output electric power obtained in this paper, should satisfy

1. "The shunt capacitance has numerical value higher than output capacitance C_{ds} of the transistor."
2. "The peak switch, voltage is lower than the highest permissible voltage of the transistor."
3. "The highest switch electric current is lower than the highest permissible current of a transistor."

Namely,

$$\begin{cases} C_{ds} < C_1 \\ V_{\max} < V_{SM} \\ I_{\max} < I_{SM} \end{cases} \quad (9)$$

When ω was given with V_{DD} , three unknown quantities, θ , D and R should be determined to obtain P_o of the formula (1). Therefore a problem of this paper is concentrated in the problem that optimum solution $\max P_o$ which meets the condition of (9). The numerical value of D is $0 < D < 1$ at the reach on the theory by a reference book [1].

In order to obtain maximum P_o , $x=(\theta, D, R)$ space was divided into $100 \times 100 \times 100$ cubics. Then (6) (7) (8) is found from the numerical value of (θ, D, R) , and it's checked whether these meet the condition of (9). It's examined whether P_o obtained by the formula (1) is highest. If it's

found higher than temporary maximum, it's recorded as the new temporary maximum. When having finished checking all combination of (θ, D, R) , remaining temporary maximum P_o will be the maximum output value at the end, and the numerical value of (θ, D, R) will be the maximum output condition.

4. A calculation example

The maximum output was calculated about two examples of actual power MOSFETS. It was calculated about power MOSFET IRF510 as the first example. These specification of the transistor and operating condition of a circuit seem to be below.

Power transistor IRF510

$$\begin{aligned} V_{DD} &= 10 \text{ V}; \\ \omega &= 2.0 \cdot \text{PI} \cdot 13.56 \text{e}+6 \text{ (i.e., 13.56 MHz)}; \\ C_1 &= C_{\text{oss}} - C_{\text{rss}} = (81-15) \cdot 1.0 \text{e}-12 \text{ F} = 66 \text{ pF}; \\ V_{\text{max}} &= 100 \text{ V}; \\ I_{\text{max}} &= 5.6 \text{ A}; \end{aligned}$$

Search in $x=(\theta, D, R)$ space gave us $\theta=-4.385 \text{e}-15 \text{ rad}$, $D=0.37$ and $R=4.467 \Omega$ and maximum output $P_o=23.509 \text{ W}$. The circuitry value of this time is $C_1=219.8 \text{ pF}$, $L=0.52 \mu\text{H}$ and $C=284 \text{ pF}$. The obtained theoretical peak switch voltage was $V_{\text{SM}}=47.938 \text{ V}$, and a theoretical peak switch electric current was $I_{\text{SM}}=5.600 \text{ A}$. The highest permissible current of a transistor was fully for a theoretical peak switch electric current, but the theoretical peak voltage was 4% lower than the permissible value.

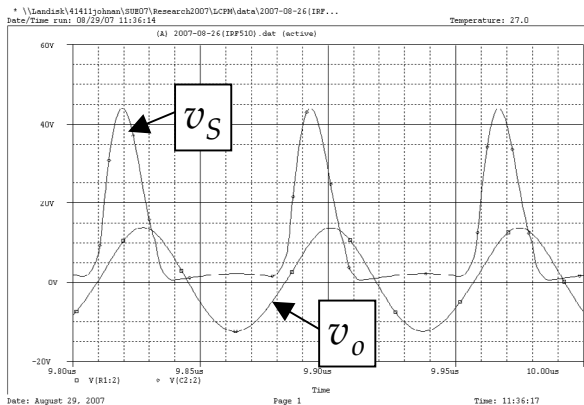


Fig. 3. Simulated waveforms of switch voltage v_S and output voltage v_o for the maximum output power with IRF510 power MOSFET.

Figure 3 is the result of Pspice simulation in the example condition. Data of a manufacturer offered was used for a spice model of IRF510. A capacitor of 160pF was added as a shunt capacitor between the drain and the source of a transistor to adjust the numerical value of the shunt

capacitance. Choke-coil was set as $L_{\text{RFC}}=2.3 \mu\text{H}$ from the formula of the reference book [2]. The switch voltage waveform on figure 3 is doing ZVS operation. The peak switch voltage was 43.2V (design value was 47.9V), and the peak switch electric current was 4.9A (design value was 5.6A). The output electric power was 17.5W.

The second example is power MOSFET IXYS DE475-120N21A. Specification of the transistor and operating condition of a circuit are as below.

Transistor IXYS DE475-102N21A

$$\begin{aligned} V_{DD} &= 250 \text{ V}; \\ \omega &= 2.0 \cdot \text{PI} \cdot 13.56 \text{e}+6; \text{ (i.e., 13.56 MHz)}; \\ C_1 &= (200-60) \cdot 1.0 \text{e}-12 = 140 \text{ pF}; \\ V_{\text{max}} &= 1000 \text{ V}; \\ I_{\text{max}} &= 24 \text{ A}; \end{aligned}$$

“ $D=0.469$, $\theta=-0.625 \text{ rad}$ and $R=15.808 \Omega$ ” were found as a result of the calculation, and $P_o=2.03 \text{ kW}$ was obtained from these. The circuitry values were $C_1=135 \text{ pF}$, $L=18.6 \mu\text{H}$ and $C=85 \text{ pF}$. A theoretical peak switch electric current was found with $I_{\text{SM}}=24.1 \text{ A}$, and the theoretical peak switch voltage was found with $V_{\text{SM}}=888.5 \text{ V}$.

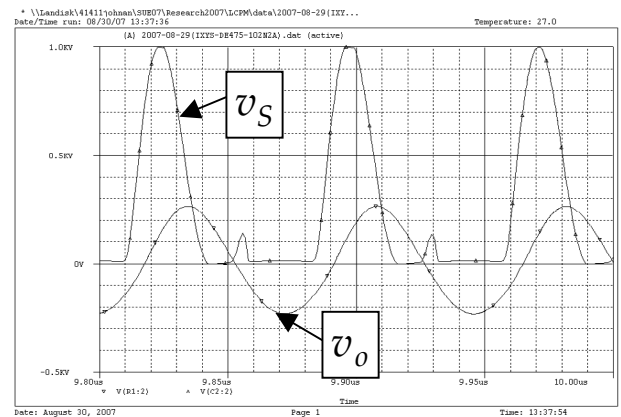


Fig. 4. Simulated waveforms of switch voltage v_S and output voltage v_o for the maximum output power with DE475-102N21A power MOSFET.

A simulation waveform is indicated on figure 4. The switch voltage waveform is doing ZVS operation mostly, but it falls in zero voltage before turn on of the switch. The switch voltage exceeds the highest permissible voltage 1kV of a transistor, but the peak value is the numerical value close to the calculation value 1kV. These errors seem to depend on nonlinearity of the shunt capacitance. The peak switch electric current was 24.37A, and the output electric power obtained from a simulation was 1.94kW.

5. A conclusion

When an optional transistor was given the way to find the condition of the class E amplifier indicated to get the maximum output electric power was shown by this paper.

References

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