Safe Operating Area Limitations in Class B Amplifiers

Hristo Zhivomirov[1]

Abstract – **The present paper describes analysis of the instantaneous power dissipated by a class B amplifier in the light of the load lines and the Safe Operating Area (SOA) limitations. Both situations of operation with steady state sinusoidal or random signals are treated, as well as working with constant complex impedance and constant resistive component of impedance.**

Keywords – **Class B amplifier, Complex load, Load lines, Safe operating area.**

I. Introduction

The study of the power parameters of the amplifier stages is a major task in the analysis and design of amplifiers. The obtained information concerns the choice of active components and the calculation of their cooling. In this paper the main point is on the SOA limitations of the active components in class B amplifiers, since this is of significant importance for their selection and properly operation but is rarely taken into account by the designers.

II. Analysis

Since the amplifiers in general case operate with complex loads the analysis must be done under these conditions. For the purposes of this paper the impedance Z_L is represented as a sum of active resistance R_L and reactive resistance (reactance) X_L which is composed of capacitance and inductance [1]:

$$\dot{Z}_L = R_L \pm jX_L = \left|\dot{Z}_L\right|.e^{j\varphi} = Z_L \angle \varphi \,, \Omega \qquad (1)$$

$$Z_L = \sqrt{R_L^2 + X_L^2} \,, \Omega; \ \varphi = arctg\left(\frac{X_L}{R_L}\right) ,\text{rad} \qquad (2)$$

where φ is a phase shift angle between the current i_C and the voltage u_{CE}.

Analysis will be done for both situations:

a) $Z_L = \sqrt{R_L^2 + X_L^2} = const.$

b) $Z_L = \sqrt{R_L^2 + X_L^2}$, at $R_L = const.$

The first case is relatively theoretical in nature, while the second covers most practical situations.

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It is convenient to express the instantaneous power dissipated by the active devices (e.g. bipolar transistors) in the area of their output characteristics $I_C = f(U_{CE})$. In this occasion the current through the device and the voltage drop across its terminals can be expressed as [2]:

$$u_{CE} = U_{cc} - u_{out} = U_{cc} - U_{out\,m}\sin(\alpha \pm \varphi) \,, \text{V} \qquad (3)$$

$$i_C = i_{out} = \frac{U_{out\,m}\sin\alpha}{Z_L} \,, \text{A} \qquad (4)$$

Here and forward the starting point ($\alpha = \omega t = 0$) is the point at which the current i_C passes through its zero value.

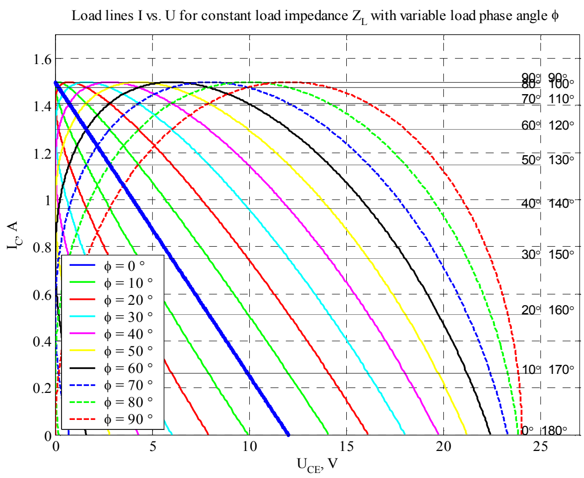

Fig. 1. Load lines at $Z_L = const.$ ($U_{cc} = U_{out\,m} = 12$ V, $Z_L = 8\ \Omega$) when the phase angle α is taken into account

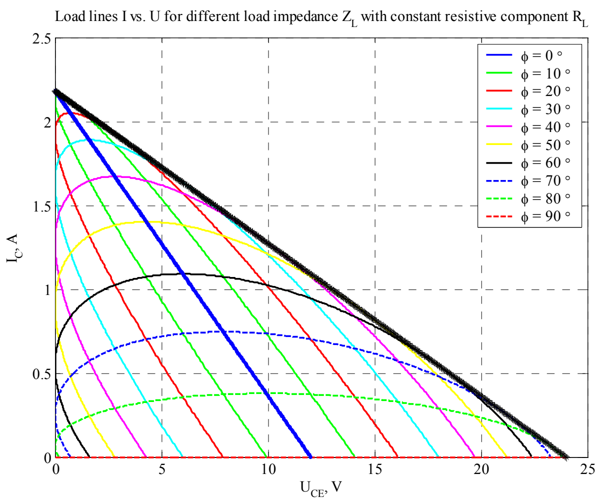

Fig. 2. Load lines at $R_L = const.$ ($U_{cc} = U_{out\,m} = 12$ V, $R_L = 5.5\ \Omega$)

By means of the last two equations a load line can be built in the field of output characteristics for both cases of operation: $Z_L = const.$ (Fig. 1) and $R_L = const.$ (Fig. 2).

The analysis of Fig. 2 shows that load line can be built tangent to the load lines at different phase angles φ, corresponding to the work with an equivalent resistance $R'_L = 2R_L$ and $U_{CEmax} = 2U_{cc}$ [2, 3].

The safe operating area (Fig. 3) is defined as the region of output characteristics of the device in which its failure-free operation is ensured.

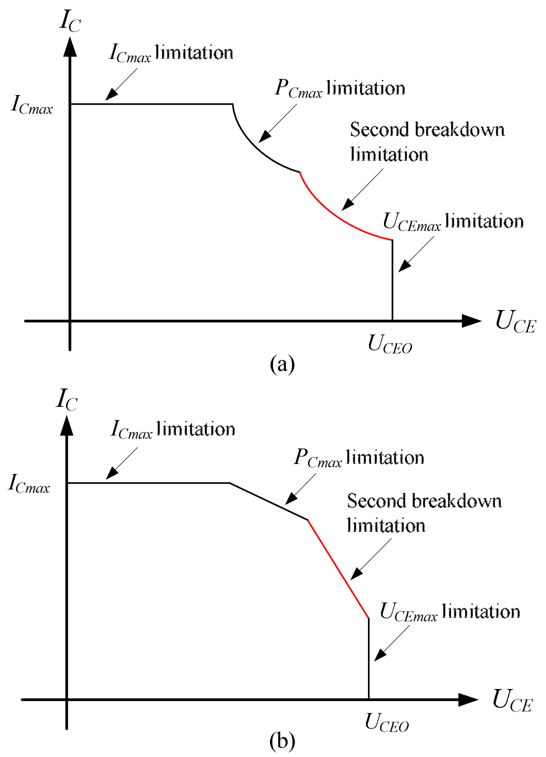

Fig. 3. Safe operating area of bipolar transistor: a) linear scale and b) log scale

The safe operation of the device depends on several limitations: the maximum current through it, the maximum power dissipation and the maximum voltage between its terminals under certain operating conditions.

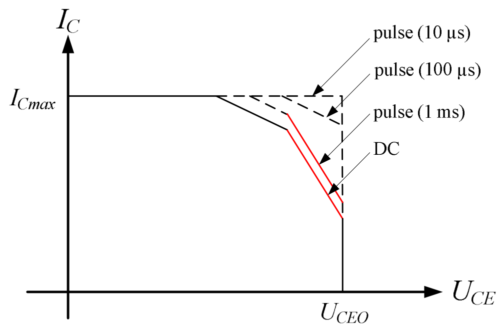

Fig. 4. Extension of SOA, when with pulse signals is worked

Bipolar transistors (BJT) unlike JFETs, MOSFETs, IGBTs, etc. are characterized by the risk of second breakdown [4], as shown in Fig. 3.

It is important to be noted the expansion of SOA when with pulse signals is operated [4] (Fig. 4) and the temperature dependence of the latter must be taken into account.

The theory and practice of signal processing [5] show that the speech and music signals have standard normal (Gaussian) distribution of the amplitudes, the density of which is described by the function [6]:

$$N(x) = \frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}}, \qquad (5)$$

the plot of whose is given in Fig. 5.

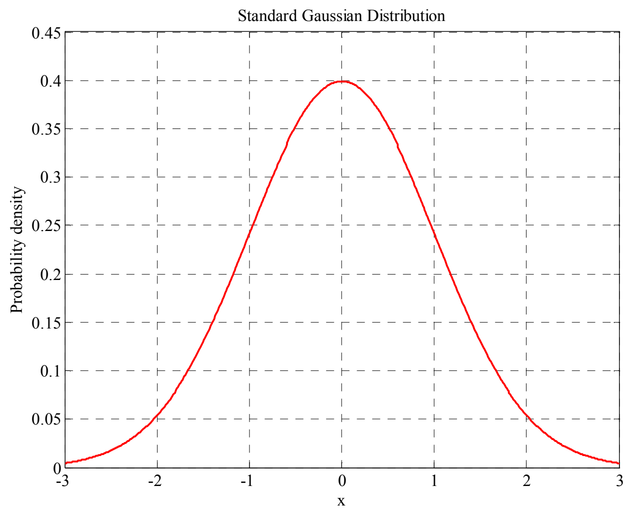

Fig. 5. Probability density of a standard normal (Gaussian) distribution

In order to evaluate the probability the instantaneous value of the random signal $x(t)$ to hit in the interval σ $[a, b]$ it's necessary to integrate the probability density function in this interval [6]:

$$P(a \le x \le b) = \frac{1}{\sqrt{2\pi}} \int_a^b e^{-\frac{x^2}{2}} dx \qquad (6)$$

In Table 1 the probability of getting into a few different confidential intervals is given.

TABLE I
STANDARD NORMAL CUMULATIVE DISTRIBUTION

Confidence interval $[a, b]$	Probability P, %
$\pm\sigma$	68.2689
$\pm 2\sigma$	95.4500
$\pm 3\sigma$	99.7300
$\pm 4\sigma$	99.9937
$\pm 5\sigma$	99.9999

It must be noted that the root mean square value U_{rms} of the random signal $x(t)$ coincides with σ [7, 8] (Fig. 6).

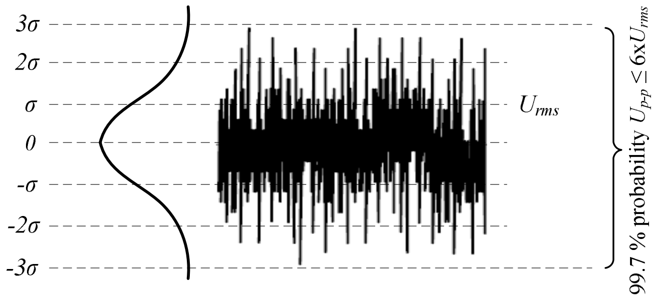

Fig. 6. Gaussian distribution of a random signal

Fig. 7 shows how to evaluate the possibility of the active element to work with a complex load.

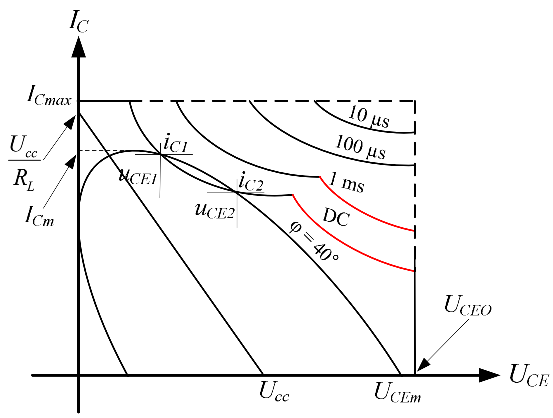

Fig. 7. Evaluation of the ability to operate with a complex load

After the load lines are drawn in the SOA according to Eqs. (3) and (4) (e.g. for values of φ at intervals of 10°), then it is necessary to calculate the residence time of the current t_i in the SOA using [1]:

$$\psi = \arcsin\left(\frac{i_C}{I_{Cm}}\right), ° \tag{7}$$

$$t_i = \frac{|\psi_1° - \psi_2°|}{360 f}, \text{ s}, \tag{8}$$

where f is the frequency of operation, for which the corresponding load line is drawn. When the phase shift φ between the voltage and the current is known, the last can be calculated as follows:

$$f \approx \frac{tg\varphi R_L C_L + 2\sqrt{L_L C_L}}{4\pi L_L C_L}, \text{ Hz}, \tag{9}$$

where: L_L – load inductance, H;

C_L – load capacitance, F.

If the frequency is outside the amplifier band further calculations are not necessary to be made.

In the same manner a t_u can be found (note that $U_{CEm} = U_{cc} + U_{out\,m}$). In this case the failure-free operation is obtained when the load line is entirely within the SOA given for the pulses with duration $t = \max(t_u, t_i)$ and duty cycle [1]:

$$\gamma \geq \gamma_{eq} = \frac{t}{T} = t \cdot f \tag{10}$$

The estimation must be done for all load lines intersect the DC SOA-curve. If the SOA is presented in logarithmic scale then the load lines also must be presented at this way (Fig. 8).

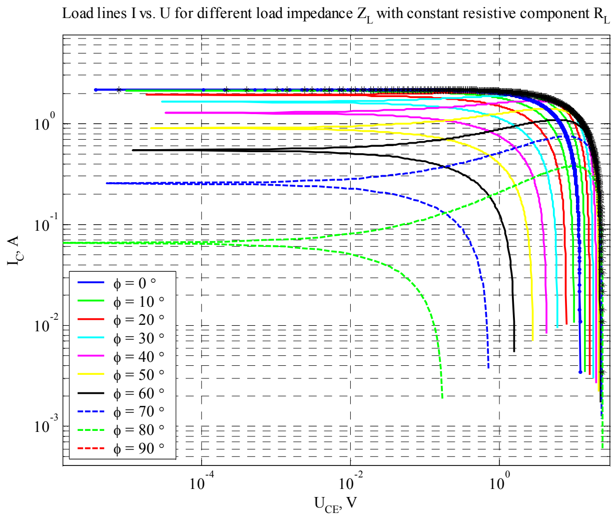

Fig. 8. Load lines at $R_L = const.$ ($U_{cc} = U_{out\,m} = 12$ V, $R_L = 5.5$ Ω) – logarithmic expression

If with random signals is worked then it is necessary to find the probability P (6) of overcoming the DC SOA-curve where:

$$a = 4\left(\frac{k_{out2}}{k_{out\,m}}\right); b = 4\left(\frac{k_{out1}}{k_{out\,m}}\right), \tag{11}$$

here k may represent current or voltage depends on which of two time intervals t_i and t_u is bigger. The coefficient before the brackets shows that confidence interval ±4σ is used, but it is possible to choose another value. Then about the equivalent duty cycle can be recorded:

$$\gamma_{eq\,rand} = \gamma_{eq} \cdot P \tag{12}$$

In conclusion it is recommended to be used a regime at which the equivalent load line is entirely within the SOA obtained for DC signal.

At the same way estimation can be made when with $Z_L = \sqrt{R_L^2 + X_L^2} = const.$ is operated.

III. Computer Simulations

Fig. 9 demonstrates the SOA of IC LM1876 – class B power amplifier. The circuit parameters are: coefficient of effective use of supply voltage $\xi = 1$, operating frequency f = 1 kHz, load $Z_L = 5.7 + j5.7\,\Omega$, phase deviation $\varphi = 45°$. The same manner of presentation is used at [9, 10].

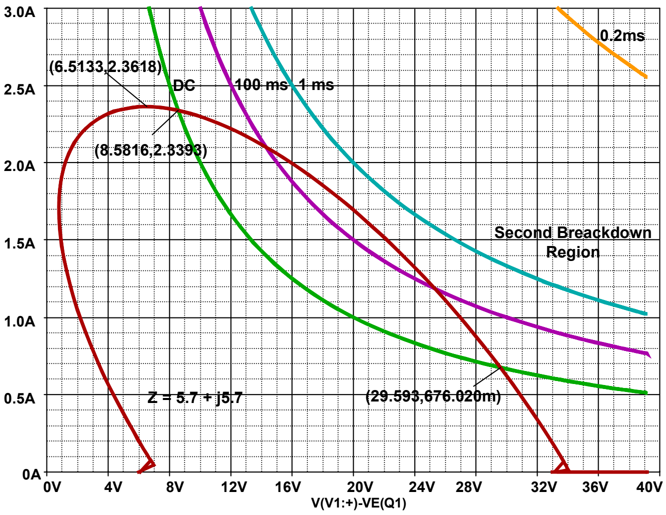

Fig. 9. SOA and load line for LM1876 operating with $R_L = const.$ (U_{cc} = 20 V, R_L = 5.7 Ω, t_c = 27°C)

When with the current is worked according to Fig. 7 then can be written:

$$\psi_1 = \arcsin\left(\frac{2.34}{2.36}\right) = 82.5°$$

$$\psi_2 = \arcsin\left(\frac{0.676}{2.36}\right) = 16.6°,$$

hence $t_i = \dfrac{82.5 - 16.6}{360 \cdot 1000} = 183\,\mu s$. Likewise $t_u = 102\,\mu s$ i.e. t_i dominates and it will be used in following expressions. Consequently the duty cycle of the equivalent pulse train is determined by $\gamma_{eq} = \dfrac{183 \cdot 10^{-6}}{1 \cdot 10^{-3}} = 0.18$. Under these conditions the amplifier could not be used, since for the utilized IC $\gamma = 0.1$, although the load line is entirely within the 200 µs SOA.

If with random signals is worked, for probability to overcome the DC SOA limitation can be written:

$$P(a \le x \le b) = 0.125,$$

where: $a = 4\left(\dfrac{0.676}{2.36}\right) = 1.5$; $b = 4\left(\dfrac{2.34}{2.36}\right) = 3.97$.

Consequently the equivalent duty cycle of the pulses is $\gamma_{eq\,rand} = 0.18 \cdot 0.125 = 0.023$. In this case, dealing with random signals, the amplifier can be used without problem.

IV. Conclusion

The problem of instantaneous power dissipation by class B amplifiers operating with complex load and steady state sinusoidal or random signals is considered. The analysis is realized using load lines and taking into account the SOA limitations.

Differences between the two regimes are marked and conclusion about parameters influencing the selection of the active components is made. Methodology for estimation of the possibility of failure-free operation is provided, based on SOA limitations and instantaneous power dissipation by the amplifier. The simulation results that confirm the theoretical statement are given. The analysis concerns the work of all active components no matter the type – BJTs, FETs, IGBTs etc.

In the statement Fig. 1 is originally presented, and the estimation methodology, Fig. 7 and Eqs. (8), (9), (11), (12) are original contribution.

This work is essential for the design and improvement of amplifier equipment as well as the theoretical analysis of amplifiers.

Consideration of the theme will continue with determination of the average power dissipation by the amplifiers when with random signal is operated.

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