On Instantaneous Power Dissipation in Class B Amplifier

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Abstract **– The present paper describes the analysis of the instantaneous power dissipation by the two active components in a class B power amplifier. Attention is paid to restrictions of the instantaneous power dissipation relations in reference literature, and the consequences of their misuse. A new generalized equation that takes into account the power dissipated by the two active devices is proposed. The theoretical statement is substantiated by Matlab® numeric computation and visualization, Cadence OrCAD® simulations and measurements of a real-world audio power amplifier performed by NI USB-6211 measurement complex.**

Keywords **– Instantaneous power, Power dissipation, Class B Amplifier, Generalized equation.**

1. Introduction

The functional circuit of power amplifier working in class B is given in Fig. 1 [1].

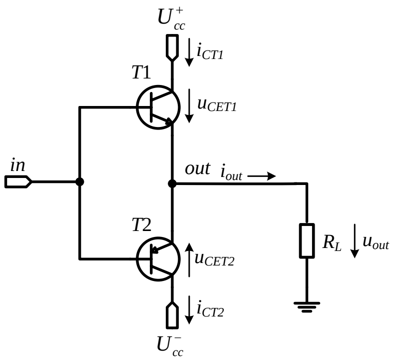

Figure. 1. Functional circuit of the power amplifier stage working in class B

The output voltage and current of the amplifier operating with sine-wave signal is described as [2]:

$$u_{out} = U_{out\,m} \sin \omega t = U_{out\,m} \sin \alpha \tag{1}$$

$$i_{out} = \frac{U_{out\,m}}{R_L} \sin \omega t = \frac{U_{out\,m}}{R_L} \sin \alpha \tag{2}$$

where U_{outm} is the amplitude of the output voltage; R_L – resistance of the load; ω – angular frequency; t – time; T – period of the signal; $\alpha = \omega t$ – phase of the signal [3].

For $0 \leq t \leq T/2$, is active the transistor connected to a positive supply rail U_{cc}^{+}. Similarly for $T/2 \leq t \leq T$, current flows through the lower arm of the amplifier [2],[4],[5]. Therefore the active regime of each transistor is determined by the period at which it is conducting [6],[10],[11]. Fig. 2.describes the process of amplification of the upper arm of the amplifier.

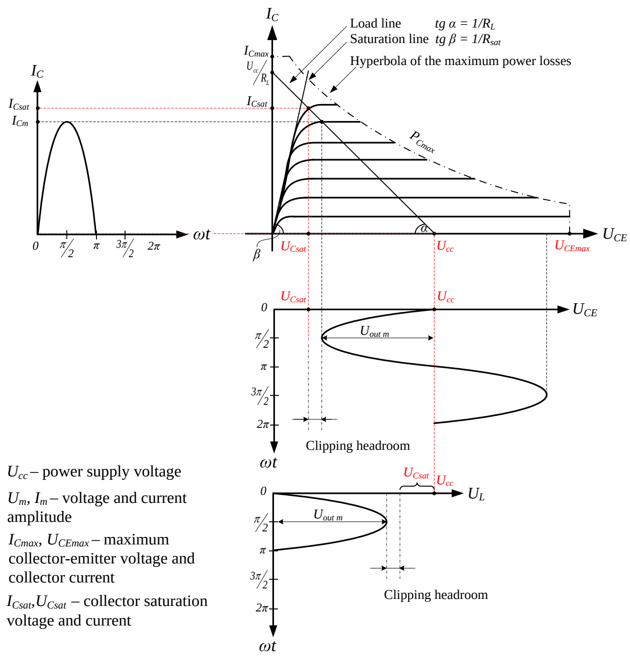

Figure. 2. Output dynamic characteristics of the upper arm transistor and the process of amplification

One should note that for the designer of audio power amplifiers (as opposed to sonar or RF amplifiers) the main design parameter is not efficiency, but rather inefficiency, i.e. the power dissipated by output active device [6]. This paper aims the instantaneous power dissipation calculation, which directly effects the calculation of average power dissipation, SOA-limitation and the selection of active components and thermal heat sinks.

2. Instantaneous power dissipation operating with resistive load

2.1. Basic relations

The power dissipated by each transistor can be represented as a product of the collector-emitter voltage drop u_{CE} and collector current i_C:

$$P_{D(inst)} = u_{CE}(t) \cdot i_C(t) \,. \quad (3)$$

For the upper arm transistor connected to the positive supply rail U_{cc}^{+} [3, 4, 5, 7]:

$$u_{CET1} = U_{cc}^{+} - u_{out}, \text{ for } 0 \le \alpha \le 2\pi \quad (4)$$

$$i_{CT1} = \begin{cases} i_{out} = I_{outm} \sin\alpha & \text{for } 0 \le \alpha \le \pi \\ 0 & \text{for } \pi \le \alpha \le 2\pi \end{cases} \quad (5)$$

and for the transistor connected to the negative rail U_{cc}^{-}:

$$u_{CET2} = U_{cc}^{-} - u_{out}, \text{ for } 0 \le \alpha \le 2\pi \quad (6)$$

$$i_{CT2} = \begin{cases} 0 & \text{for } 0 \le \alpha \le \pi \\ i_{out} = I_{outm} \sin\alpha & \text{for } \pi \le \alpha \le 2\pi \end{cases} . \quad (7)$$

One can assume $U_{cc} = U_{cc}^{+} = -U_{cc}^{-}$ [2].

The signs in Eqs. (4) ÷ (7) are in accordance to the established rules in electrical engineering, e.g. currents entering the node – plus sign, for voltages from high potential to low potential – plus sign, and vice-versa.

Table 1.shows some parameters of a class B amplifier operating with resistive load.

Table 1.Some parameters of the circuit from Fig. 1.

α / Parameter	$0 \le \alpha \le \pi$		$\pi \le \alpha \le 2\pi$	
	$T1$	$T2$	$T1$	$T2$
$\lvert u_{CE} \rvert$	$< U_{cc}^{+}$	$> \lvert U_{cc}^{-} \rvert$	$> U_{cc}^{+}$	$< \lvert U_{cc}^{-} \rvert$
i_C	$= i_{out}$	$= 0$	$= 0$	$= i_{out}$
$P_{D(inst)}$	> 0	$= 0$	$= 0$	> 0

It can be shown (Fig. 2, Fig. 3) that:

$$\lvert u_{CE} \rvert \begin{cases} \le 2U_{cc} - U_{CEsat} \\ \ge U_{CEsat} \end{cases} \quad (8)$$

whereU_{CEsat} is the collector – emitter saturation voltage of the transistors.

The relation between the output current of the amplifier and the collector current of each transistor is:

$$i_{out} = i_{CT1} + i_{CT2} \,. \quad (9)$$

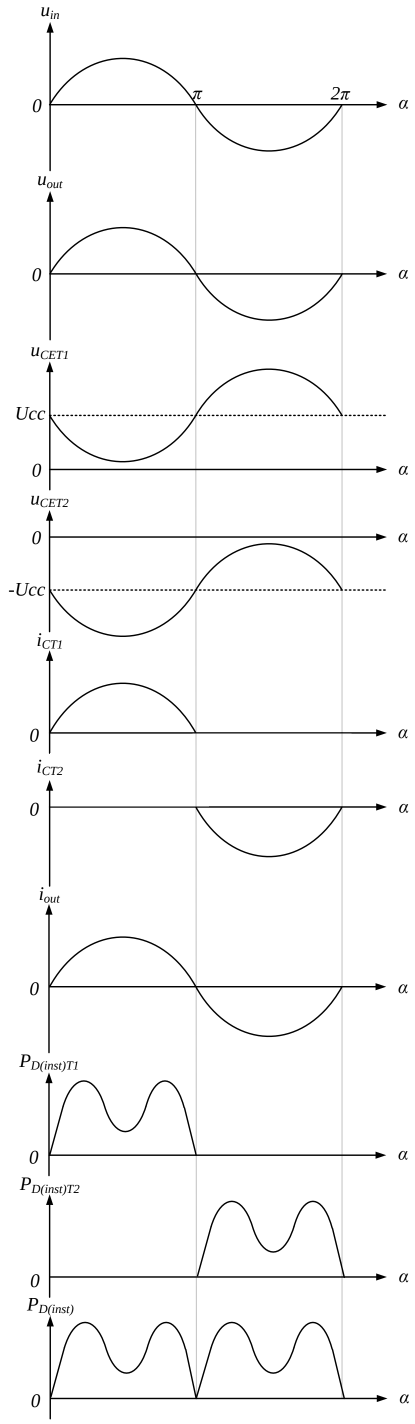

Figure 3. Graphical representation of the voltages, currents and instantaneous dissipated power of the class B amplifier

By means of substitution of Eqs. (4) ÷ (7) into (3) for the instantaneous power dissipation of the amplifier can be written:

- for the upper arm of the amplifier [2], [6]:

$$P_{D(inst)T1} = \left(U_{cc} - U_{out\,m} \sin\alpha\right) \cdot i_{CT1} = = \left(U_{cc} - U_{out\,m} \sin\alpha\right) \cdot \frac{U_{out\,m}}{R_L} \sin\alpha \quad (10)$$

for $0 \le \alpha \le \pi$; $P_{D(inst)T1} = 0$ for $\pi \le \alpha \le 2\pi$.

- for the lower arm:

$$\begin{aligned} P_{D(inst)T2} &= \left(-U_{cc} - U_{out\,m}\sin\alpha\right)\cdot i_{CT2} \\ &= \left(-U_{cc} - U_{out\,m}\sin\alpha\right)\cdot \frac{U_{out\,m}}{R_L}\sin\alpha \end{aligned} \quad (11)$$

for $\pi \le \alpha \le 2\pi$; $P_{D(inst)T2} = 0$ for $0 \le \alpha \le \pi$.

2.2. Generalized equation

In terms of more compact representation of Eqs. (10) and (11), Eqs. (5) and (7) are transformed as follows:

- for the upper arm of the amplifier [4, 8]:

$$i_{CT1} = \frac{I_{outm}\sin\omega t + \left|I_{outm}\sin\omega t\right|}{2R_L} \text{ for } 0 \le \alpha \le 2\pi \quad (12)$$

- for the lower arm:

$$i_{CT2} = \frac{I_{outm}\sin\omega t - \left|I_{outm}\sin\omega t\right|}{2R_L} \text{ for } 0 \le \alpha \le 2\pi \,. \quad (13)$$

Eqs. (10) and (11) become:

- for the upper arm:

$$P_{D(inst)T1} = \left(U_{cc} - U_{out\,m}\sin\alpha\right)\cdot\frac{U_{out\,m}}{2R_L}\left(\sin\alpha + \left|\sin\alpha\right|\right) \quad (14)$$

for $0 \le \alpha \le 2\pi$.

- for the lower arm:

$$P_{D(inst)T2} = \left(U_{cc} - U_{out\,m}\sin\alpha\right)\cdot\frac{U_{out\,m}}{2R_L}\left(\sin\alpha - \left|\sin\alpha\right|\right) \quad (15)$$

for $0 \le \alpha \le 2\pi$.

To summarize, using Eqs. (3) and (9) and with reference to Fig. 3, a new generalized relation is proposed about the total instantaneous power dissipated by the amplifier (by the two arms):

$$\begin{aligned} P_{D(inst)} &= P_{D(inst)T1} + P_{D(inst)T2} = u_{CET1}\cdot i_{CT1} + u_{CET2}\cdot i_{CT2} = \\ &= \left(U_{cc} - u_{out}\right)\cdot i_{CT1} + \left(-U_{cc} - u_{out}\right)\cdot i_{CT12} = \\ &= \left[\operatorname{sgn}\left(i_{out}\right)U_{cc} - u_{out}\right]\cdot i_{out} \end{aligned} \quad (16)$$

where the signum function is used [9]:

$$\operatorname{sgn}(x) = \begin{cases} -1 & \text{for } x < 0 \\ 0 & \text{for } x = 0 \\ +1 & \text{for } x > 0 \end{cases} \,. \quad (17)$$

When the amplifier operates with resistive load and sine-wave signal:

$$P_{D(inst)} = \left[\operatorname{sgn}\left(\sin\alpha\right)U_{cc} - U_{out\,m}\sin\alpha\right]\cdot\frac{U_{out\,m}}{R_L}\sin\alpha \quad (18)$$

for $0 \le \alpha \le 2\pi$.

If the coefficient of effective use of supply voltage is assumed to be $\xi = \frac{U_{out\,m}}{U_{cc}}$ [4], then Eq. (18) can be rewritten as:

$$P_{D(inst)} = \frac{U_{cc}^2}{R_L}\left[\operatorname{sgn}\left(\sin\alpha\right)\xi\sin\alpha - \xi^2\sin^2\alpha\right] . \quad (19)$$

The results of the analysis of Eqs. (10), (14) and (18) are represented in Fig. 4.

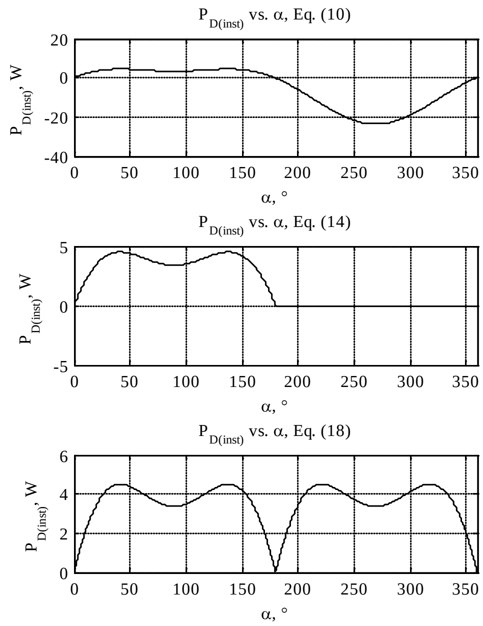

Figure. 4. Graphical representation of the analysis of Eqs. (10) and (14), as well the author's Eq. (18) for $0 \le \alpha \le 2\pi$ and U_{cc} = 12 V, R_L = 8 Ω, U_m = 9 V.

3. Amplifier Simulation

Computer simulation using Cadence®OrCAD® software is provided in order to verify the theoretical statement and to illustrate the process of amplification. Simulation test circuit is shown in Fig. 5. Attention is paid to the collector-emitter voltage u_{CE} and the collector current $i_C$of the transistors (blue probes for the upper-arm and red probes for the lower-arm). Several periods of the signals is shown, so that one can track the changes of the signals in time domain[12],[13].

In Fig. 6 the simulation results are illustrated for the upper and lower arm of the amplifier. One can note that u_{CE} of each transistor is oscillating about its power supply voltage and the minimum of u_{CE} corresponds to maximum of u_{out} and vice-versa. In Fig. 6 (bottom) the results for instantaneous power dissipation are shown, that correspond to these obtained by the author's Eqs. (16) and (18).

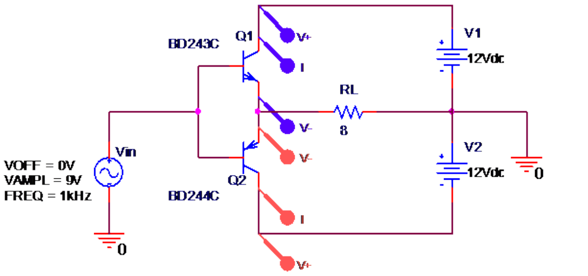

Figure. 5. Test circuit for simulation of class B push-pull amplifier

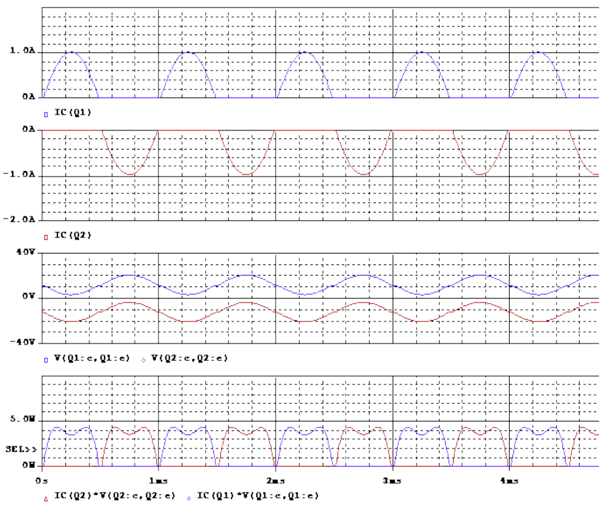

Figure. 6. Results from the simulation of class B push-pull amplifier (i_{CT1}, i_{CT2}, u_{CET1}, u_{CET2}, $P_{D(inst)T1}$, $P_{D(inst)T2}$)

4. Amplifier measurements

A measurement of real-world class B amplifier has been made and the results fully correspond to the Eq. 18.

The measured amplifier is based on integral circuit LM3886 (Hi-Fi audio power amplifier) and has the following parameters (one and the same as the simulation circuit):

- Power supply voltage U_{cc}= 12 V;
- Resistive load R_L = 8 Ω;
- Test signal: sine-wave (f=1 kHz, U_m= 9 V).

The results of the measurement are plotted in Fig. 7. One should note there is no synchronization between simulation and measurement results, since the last begin in arbitrary moment.

The measurements are made by measurement complex NI USB-6211 and author's Matlab® software, according to measurement setup shown in Fig. 8 (where measurement connection is shown only for the upper arm of the amplifier), similar to this in [14].

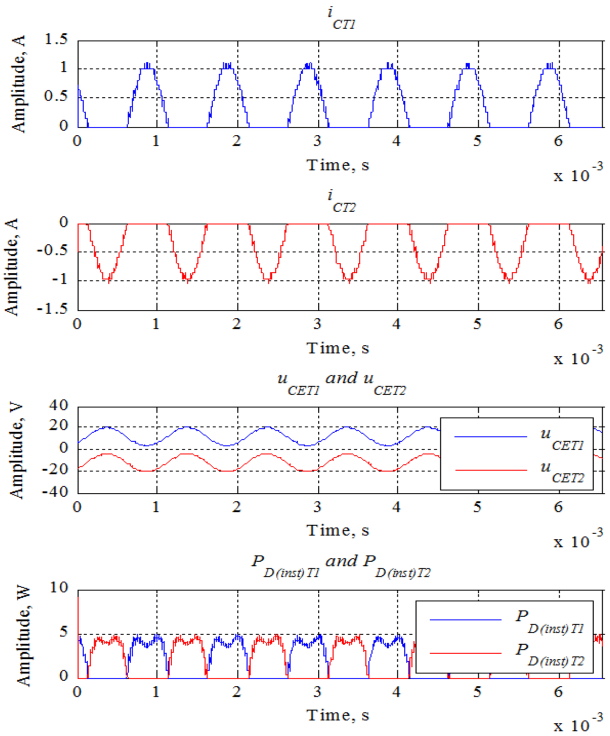

Fig. 7. Results from the measurement of real-world class B push-pull solid state audio power amplifier

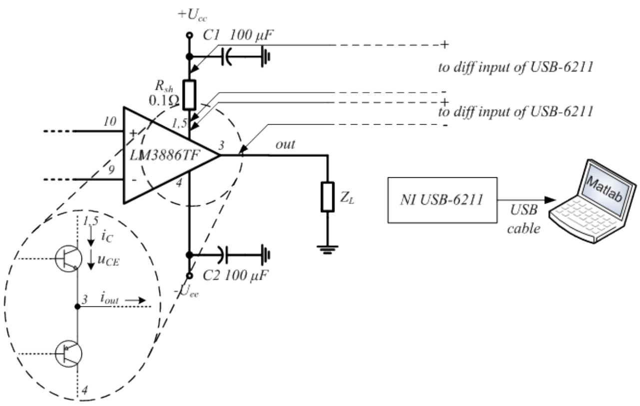

Figure. 8. Measurement setup for measurement of real-world class B push-pull solid state audio power amplifier

5. Conclusion

It should be noted that the results in Fig. 4 obtained by Eq. (10) for $\pi \leq \alpha \leq 2\pi$ are erroneous. Hence references [2],[6] must be used very carefully, as far as there is no explanation on what are the restrictions of Eq. (10), e.g. it holds true only for $0 \leq \alpha \leq \pi$.

Results in Fig. 4 obtained by Eq. (14) are true for $0 \leq \alpha \leq 2\pi$, but concern the operation only of the upper arm of the amplifier, and Eq. (15) – only the lower arm, respectively.

The proposed Eq. (18) describe the power dissipation of the two active components of the amplifier, e.g. the whole class B amplifier device for the full cycle of operation ($0 \leq \alpha \leq 2\pi$) as shown in Fig. 4. This is of great significance, especially for integrated solid state power amplifiers.

The comparison of graphical representation of Eq. (18) in Fig. 4, with simulation and measurement results about $P_{D(inst)T1}$, $P_{D(inst)T2}$in Fig. 6 and Fig. 7 confirms not only the qualitative aspect of the proposed expression but also the quantitative one.

The generalized Eq. (16) gives a new look on the instantaneous power dissipation of the class B power amplifiers and is conductive to further examination of the subject. Further considerations concerning a mathematical modeling of power parameters of class B amplifier will be given in future work, including the operation of amplifiers with stochastic signals as music or speech.

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