3D Simulation of Heat Behavior of Transistor in Amplifier Power Stage

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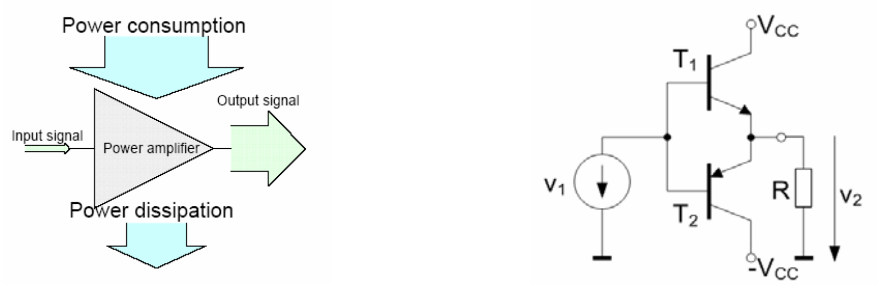
Abstract

The paper presents dynamic analysis of power condition in push-pull transistor stage designed in class B. The thermal power conditions of output transistors have been explored. Transistors of push-pull output stage with simple cooler have been simulated on equivalent 3D thermal model. Parametric thermal simulation has been applied to the model.

1. Description of push-pull power transistor stage

The power transistor amplifier amplifies a signal and in this way distributes required energy into an electric power appliance. Output power P_2 and appliance resistance R determine amount of necessary energy that power source supplies into the amplifier. Energy flux in a power amplifier is shown in Fig. 1. As can be seen, a considerable part of energy from supply source converts into a heat. It is very important the amplifier has got high efficiency that significantly decreases thermal losses.



Obr. 1. Energy flux in a power amplifier and the basic diagram of power stage

The amplitudes of output electric quantities of the power amplifier in Fig.2 are approximately equal to maximal values of quiescent and supply electric quantities of the transistor.

The operating point P of an amplifier in class B lies at the place where collector current descends to zero. Therefore, the collector current $I_{CP}=0$, $I_{BP}=0$ in the output characteristics of the transistor in Fig. 2. The equation for the load resistor R is:

$$R = \frac{V_{CC}}{I_{c\max}} \tag{1}$$

The average value of collector current of one of transistors is:

$$\overline{I_C} = \frac{1}{2\pi}\int_0^{\pi} I_{c\,max}.sin\,\omega t.d\omega t \tag{2}$$

The dc input power supplied from power source is:

$$P_{js} = \frac{V_{CC}.I_{c\max}}{\pi} \tag{3}$$

The ac power delivered to the load by each transistor is given by equation:

$$P_2 = \frac{1}{2}\cdot\frac{V_{c\max}}{\sqrt{2}}\cdot\frac{I_{c\max}}{\sqrt{2}} \tag{4}$$

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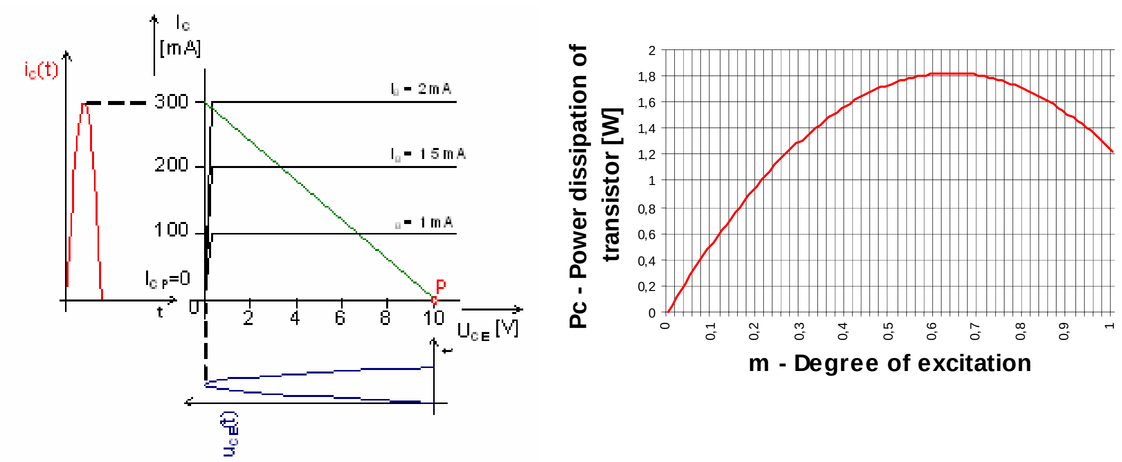
The efficiency of the power stage with operating point in class B is:

$$\eta_B = \frac{P_2}{P_{js}} = \frac{\pi}{4} \cdot \frac{V_{c\max}}{V_{CC}} \tag{5}$$



Obr. 2. The quiescent operating point in output characteristics of one of power transistors in class B and diagram of power dissipation in dependence on excitation

At full excitation, when the amplitude of voltage $V_{c\max}$ is equivalent to supply voltage V_c and transistors are parallel-connected to power source, the efficiency of power stage in class B is 78%.

Push-pull power stages are designed in various ways. They generally consist of two complementary or no complementary transistors. Each of transistors spends half of power dissipation. Fig. 3 illustrates the basic layout of power stage. Fig. 2 explains function of the amplifier. Quiescent operating point is set in class B. It means that any transistor does not conduct a current (the base current is zero). The collector voltage of transistors is $V_c = \pm V_{CC}$. The voltage $V_{c\max}$ is derived from the change of $I_{c\max}$ current of the load resistor.

The amplitude of collector voltage changes depending on excitation m within the interval 0 to $|V_{CC}|$. The dynamic range represents the excitation coefficient m:

$$m.|V_{CC}| = V_{c\max} \qquad m \in \langle 0,1 \rangle \tag{6}$$

The collector current depends on the excitation of an amplifier:

$$I_{c\max} = \frac{m.V_{CC}}{R}, \tag{7}$$

R – load resistance.

The average value of the current supplied from power source V_{cc} is:

$$\overline{I_C} = \frac{1}{2\pi}\int_0^{\pi} I_{c\max}.\sin\omega t.d\omega t = \frac{I_{c\max}}{\pi} = \frac{m.V_{CC}}{\pi.R} \tag{8}$$

The dc input power supplied from power source into the push-pull power stage is:

$$P_{js} = \frac{m.V_{CC}^2}{\pi.R} \tag{9}$$

The output power of the load R is:

$$P_2 = \frac{V_2^2}{2R} = \frac{m^2.V_{CC}^2}{2R} \tag{10}$$

Each of transistors spends half of power P_2 (10). The collector dissipation of one transistor expressed as function of transistor excitation is:

$$P_C(m) = P_{js} - \frac{P_2}{2} = \frac{V_{CC}^2}{R}\left(\frac{m}{\pi} - \frac{m^2}{4}\right) \tag{11}$$

The maximum collector dissipation is at excitation coefficient $m = \frac{2}{\pi}$ and is:

$$P_{C\max} = \frac{V_{CC}^2}{\pi^2 R} \tag{12}$$

The graphical representation of collector dissipation depending on transistor excitation is in Fig. 2. The representation is created by the supply voltage V_{CC}=12 V and resistor R = 8 Ω.

2. The transfer of heat in technical practice

The heat or the thermal energy is the internal energy that a body accepts or passes to other body.

The transfer of heat is possible by:

- Conduction (is typical for heat transfer in solid materials)
- Convection (appears in liquid and gassy materials)
- Radiation (appears at higher temperatures)

The mathematical model of heat transfer by conduction describes the next temperature equation:

$$\delta_{ts} \cdot \rho . C_p \frac{\partial T}{\partial t} - \nabla\left(k \nabla T\right) = Q \tag{1}$$

δ_{ts} is a time-scaling coefficient,
ρ is the density of materials,
C_p is the heat capacity of materials,
Q is the heat source (or sink),
k is the thermal conductivity tensor,
T is temperature,
t is time.

Normal component of heat flux in external boundary elements is:

$$n\left(k \nabla T\right) = q_0 + h\left(T_{inf} - T\right) + C_{const}\left(T_{amb}^4 - T^4\right) \tag{2}$$

Specify q_0 to represent a heat flux that enters the domain.

$h(T_{inf} - T)$ models convective heat transfer with the surrounding environment, where h is the heat transfer coefficient and T_{inf} is the ambient bulk temperature. The value of h depends on the geometry and the ambient flow condition, for example:

$$h = 5 + 17 * \left(v + 0.1\right) \wedge 0.66 \tag{3}$$

$C_{const}\left(T_{amb}^4 = T^4\right)$ models radiation heat transfer with the surrounding environment. T_{amb} is the temperature of the surrounding radiation environment, which might differ from T_{inf}. C_{const} is the product of the surface emissivity ε and the Stefan-Boltzmann constant $\sigma = 5.669 \cdot 10^{-8}$ W/m^2/K^4 (with the same unit as the Stefan-Boltzmann constant):

$$C_{const} = \varepsilon \cdot \sigma \tag{4}$$

3. Results of 3D simulation of thermal operation of transistor in the power stage in class B

Geometrical model of the transistor power stage in Fig. 3 contains the complementary couple of transistors, as indicated in the basic diagram in Fig. 1. The transistors are in package TO 220. They are situated on simple cooler. The cooler has a rectangular shape with dimensions 60*35*1 mm and is made from aluminum material. The shape of silicon of an active transistor is block with 4*4 *0.4 mm dimensions.

The parametric stationary solver depends on the degree of excitation m within the interval 0÷1. The solver is used in application mode Heat transfer by conduction of Comsol Multiphysics. The collector power dissipation of one transistor is calculated from the supply voltage and from the load resistor equably for the whole volume of a chip. The temperature of surroundings is 25 °C. The model applies natural way of cooling.

The solution result is shown in Fig. 4. The graphical output describes the temperature field of power stage. The signal excitation of power stage m = 0,1. The surface temperature of simulated physical model is within the interval 32,8 °C to 39,6 °C.

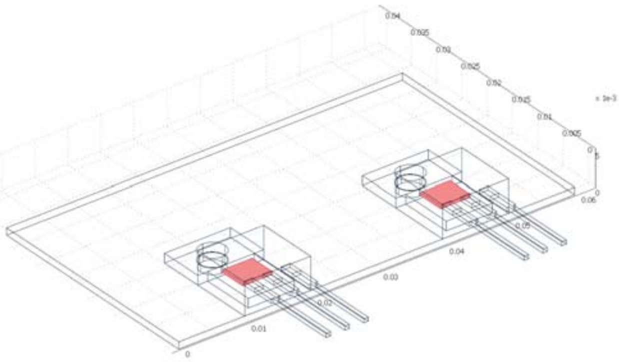


Fig. 3. Geometrical model of a power amplifier

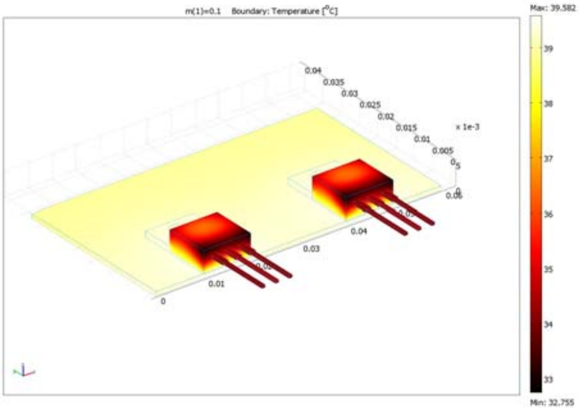


Fig. 4. Boundary temperature field of the power amplifier at m = 0.1

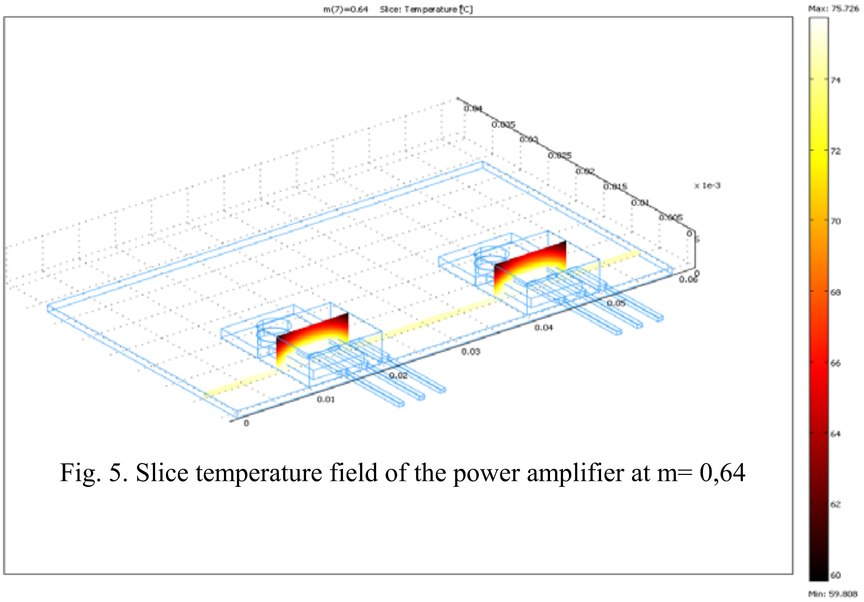


Fig. 5. Slice temperature field of the power amplifier at m= 0,64

The highest heat dissipation of transistor is when the signal excitation achieves the value m=0,64. The situation is visible in Fig. 5 . Fig. 5 shows the temperature of slice of simulated model in steady state within interval 59,8 °C to 75,7 °C. The temperature of chip does not exceed 76 °C, as indicated in Fig. 5.

Acknowledgement

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