OPERATING POINT STABILITY OF COMPLEMENTARY SYMMETRY POWER AMPLIFIERS

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Transistorized power amplifiers can be operated in a wide temperature range only if the operating point of the power transistors is kept at a constant value. The current I_C of the operating point depends on the base-to-emitter voltage U_{BE} determined by the circuit used for biasing and on the junction temperature T_j. The junction temperature is

$$T_j = T + \Theta_{ja} P_d , \tag{1}$$

where

T is the ambient temperature [°K],
Θ_{ja} is the resultant thermal resistance between transistor junction and ambient temperature, [°K/W]
P_d is the power dissipated by the transistor.
Without input signal the dissipated power is

$$P_d = I_C \cdot U_{CE} . \tag{2}$$

Thus, the ambient temperature and the dissipation affect the junction temperature of the transistor and thereby the current I_C of the operating point. If the current of the operating point is not sufficiently independent of temperature, a thermal feedback arises. As a consequence, the increase of the junction temperature will exceed that of the ambient temperature and even a thermal runaway may occur. Fig. 1 shows the relationship between temperature T_j and ambient temperature T, for a temperature-dependent, and a constant current I_C. The highest ambient temperature is permissible with a temperature-independent current I_C. The first part of our investigation will examine under which conditions the current I_C can be made constant without input signal.

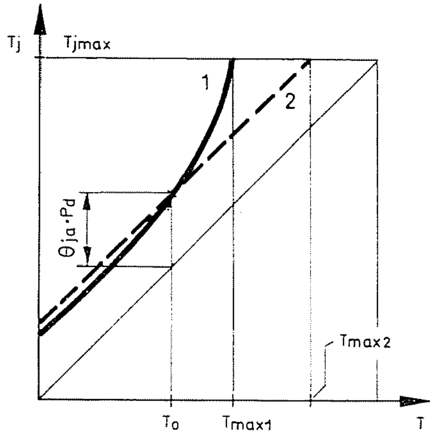


Fig. 1. Change of the junction temperature vs. ambient temperature, for temperature-dependent I_E (1) and constant I_E (2)

1. Stabilization of the collector current

A good efficiency can only be expected from a power amplifier with a relatively low emitter resistance R_E. Consequently, the collector current I_C can be kept at a constant level only if the base potential of the operating point is made temperature-dependent (with a negative temperature coefficient).

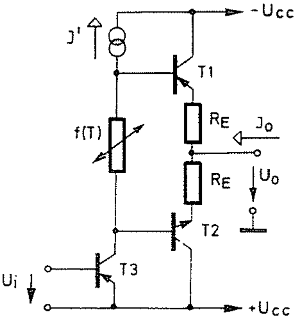


Fig. 2. Circuit diagram of a complementary symmetry power amplifier

Fig. 2 shows the scheme of a complementary symmetry power amplifier and its driver stage (transistor T3). In this system the currents of output transistors T1 and T2 must be equal at the operating point. This requirement is met if $I_0 = 0$ without input signal.This can be realized by the capacitive coupling of the load, or by a negative voltage feedback adjusting the condition $U_0 = 0$ without input signal.

The biasing component which has a negative temperature coefficient may be a thermistor, one or more forward biased dioda(s), or an appropriately coupled transistor (Fig. 3). In the following part only the latter solution will be considered, since this has the most advantageous properties, namely:

a) Its temperature dependence suits to keep the current of the power transistors at a constant value in a wide temperature range.

b) It has a low dynamic resistance.

c) It makes possible to vary the biasing by adjusting R_1 and R_2.

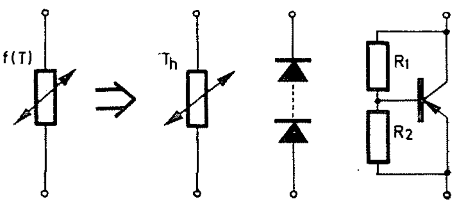


Fig. 3. Circuit elements for biasing the temperature-dependent operating point: *a)* thermistor, *b)* diodes biased in forward direction, *c)* transistor circuit.

It is required for all the three solutions that the transistors have the best possible thermal coupling with each other and with the temperature-dependent component. This means that they have to be mounted close to each other on a common heat sink. This way the junction temperature T_j of the temperature-dependent component — hence compensating transistor — will be identical with the temperature T_s of the heat sink, since it has a negligible own dissipation.

The thermal coupling between the compensating transistor and the junctions of the power transistors can be characterized by the temperature attenuation between the junction and the heat sink:

$$\gamma = \frac{T_s - T}{T_j - T} . \tag{3}$$

Due to the nearly identical thermal resistances of the transistors, also their junction temperatures will be similar. In the following calculation the junction temperatures will be considered equal at a value T_j for both transistors:

$$T_j = \frac{T_{j1} + T_{j2}}{2} . \tag{4}$$

Thus, according to Fig. 4, the thermal coupling factor will be:

$$\gamma = \frac{4\Theta_{sa}}{4\Theta_{sa} + \Theta_{js1} + \Theta_{js2}} . \tag{5}$$

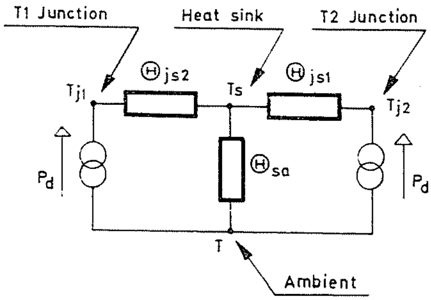


Fig. 4. Simplified thermal equivalent circuit of the power transistors

Under usual cooling conditions the value of the thermal coupling factor is between 0.2 and 0.5, and decreases with the improvement of cooling. This is not favourable for the thermal stabilization, since the compensating component is most susceptible to the change in the junction temperature of the transistor for $\gamma = 1$. From among the contradictory requirements, it appears reasonable to ensure good cooling (low Θ_{sa}) and to allow for a relatively low γ value.

$\gamma = 1$ can be fairly well approached by integrated circuits where the output transistors and the compensating transistors are built into a common chip.

On the basis of equivalent circuits the thermal resistance Θ_{ja} necessary for the calculation of the junction temperature T_j can be written as

$$\Theta_{ja} = 2\Theta_{sa} + \frac{\Theta_{js1} + \Theta_{js2}}{2} . \tag{6}$$

With the above quantities the temperature T_s of the heat sink will be:

$$T_s = T + \gamma \Theta_{ja} P_d . \tag{7}$$

2. Temperature-dependence of the biasing circuit

Neglecting the voltage drop $I_B r_{BB'}$ the potential U_{EB} of a transistor will be

$$U_{EB} \cong U_T \ln \frac{I_E}{I_S} , \tag{8}$$

where U_T and I_S are quantities depending on the junction temperature:

$$U_T = \frac{k}{q} T_j \tag{9}$$

$$I_S = I_{SO}\, e^{b(T_j - T_0)} . \tag{10}$$

Substituting (9) and (10) into (8):

$$U_{EB} \cong T_j \frac{k}{q} \left[\ln \frac{I_E}{I_{SO}} - b(T_j - T_0) \right], \tag{11}$$

where: $b \simeq 0.1$ 1/°K in Ge transistors
$b \simeq 0.15$ 1/°K in Si transistors
$k/q = 8.6 \cdot 10^{-5}$ $V/°K$

current I_{SO} is the value of current I_S at room temperature T_0. Thus

$$I_{SO} = I_{CBO}\big|_{T=T_0} \beta_I .$$

Apply the above formulas to the compensating circuit (Fig. 5). For better differentiation, in the following part the quantities of the circuit will be marked by commas. Assume:

$$U'_{EB} = \frac{U_K}{\delta}, \tag{12}$$

where

$$\delta \cong \frac{R_1 + R_2}{R_2} \quad \text{if} \quad I'_B \ll I_R. \tag{13}$$

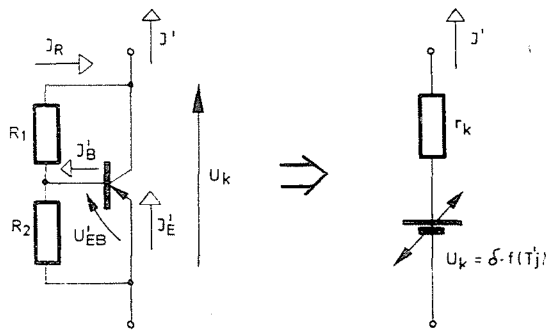


Fig. 5. Compensating transistor circuit and its equivalent circuit

From Eqs (11) and (12) the voltage drop across the two-pole can be written as

$$U_K = \delta T'_j \frac{k}{q} \left[\ln \frac{I'_E}{I_{SO}} - b'(T'_j - T_0) \right], \tag{14}$$

where

$$I'_E \cong I', \quad \text{if} \quad I_R \ll I_E.$$

It is seen that by means of resistors R_1 and R_2 the value of U_K can be changed without any change in its relative temperature dependence.

Without the details of the deduction the dynamic resistance of the two-pole will be:

$$r_K = \frac{\Delta U_K}{\Delta I'} \cong (R_1+R_2)\times\delta\,\frac{U_T'}{I_E'}\,. \tag{15}$$

3. Temperature dependence of the complete output stage

Next problem is to express the operating point current I_E of the power transistors, using the previous results. The biasing of the output stage is shown in Fig. 6. The voltages U_{BE} of transistors T1 and T2 are assumed to be equal

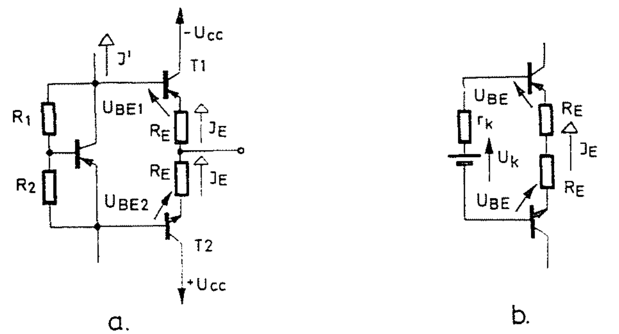


Fig. 6. Biasing of the power transistors (a), and simplified equivalent circuit (b)

by calculating with a common current I_{SO} instead of the saturation currents I_{SO1} and I_{SO2}. Then

$$I_{SO} = \sqrt{I_{SO1}\,I_{SO2}}\,. \tag{16}$$

Neglecting the resistance r_k the loop equation of the common base-emitter circuit of the two transistors can be written as

$$U_K = 2(U_{EB}+I_E R_E)\,. \tag{17}$$

Substituting Eqs (14) and (11) of voltages U_k and U_{EB}, and taking the statement $T_j' = T_s$ into consideration, the following relationship will be obtained:

$$\frac{\delta}{2}\,\frac{k}{q}\,T_s\left[\ln\frac{I_E'}{I_{SO}'} - b'(T_s-T_0)\right] = \frac{k}{q}\,T_j\left[\ln\frac{I_E}{I_{SO}} - b(T_j-T_0)\right] + I_E R_E. \tag{18}$$

Other parts of the circuit ensure that, for a constant supply voltage, the current I' is nearly constant. Since $I_E' \simeq I'$, the logarithmic member in the left-hand side of (18) is constant. Let A' be the symbol for its value:

$$A' = \ln\frac{I_E'}{I_{SO}'}\,. \tag{19}$$

The logarithmic member in the right-hand side of (18) is not constant, but it can be replaced by a linear approximation.

$$\ln \frac{I_E}{I_{SO}} = A + B I_E , \tag{20}$$

where

$$A = \ln \frac{I_{EO}}{I_{SO}} - 1, \quad B = \frac{1}{I_{EO}} . \tag{21),(22}$$

Current I_{EO} is the value of the operating point current I_E adjusted at room temperature T_0.

Let us also take into consideration that $I_C \simeq I_E$ and the T_s and T_j values are given by relationships (1), (2) and (7). This way we get a form of (18) where the I_E value is affected only by T, R_E and δ, since the transistors have been suitably chosen (I_{SO}, b, I'_{SO}, b'), the data of the operating point (I_{EO}, U_{CE}, I') have been assumed, and the cooling conditions (γ, Θ_{ja}) are known.

$$\begin{aligned} &\frac{\delta}{2} \frac{k}{q} (T + \gamma \Theta_{ja} I_E U_{CE}) [A' - b'(T - T_0 + \gamma \Theta_{ja} I_E U_{CE})] = \\ &= \frac{k}{q} (T + \Theta_{ja} I_E U_{CE}) [A + I_E B - b (T - T_0 + \Theta_{ja} I_E U_{CE})] + I_E R_E . \end{aligned} \tag{23}$$

As it has been prescribed that I_E is equal to I_{EO} at room temperature ($T = T_0$), at an assumed value of R_E this operating point will be obtained as:

$$\delta = 2 \frac{(T_0 + I_{EO} U_{CE} \Theta_{ja}) (I_{EO} U_{CE} \Theta_{ja} b - A - 1) - I_{EO} R_E \frac{q}{k}}{(T_0 + I_{EO} U_{CE} \Theta_{ja} \gamma) (I_{EO} U_{CE} \Theta_{ja} \gamma b' - A')} . \tag{24}$$

Further on, the behaviour of the function $I_E(T)$ with different R_E values has to be examined. According to Eq. (24), also δ has to be changed if the emitter resistance R_E is changed in order that the current at room temperature be the prescribed I_{EO} without any change.

4. Conditions for adjusting the current of the operating point independently of the ambient temperature

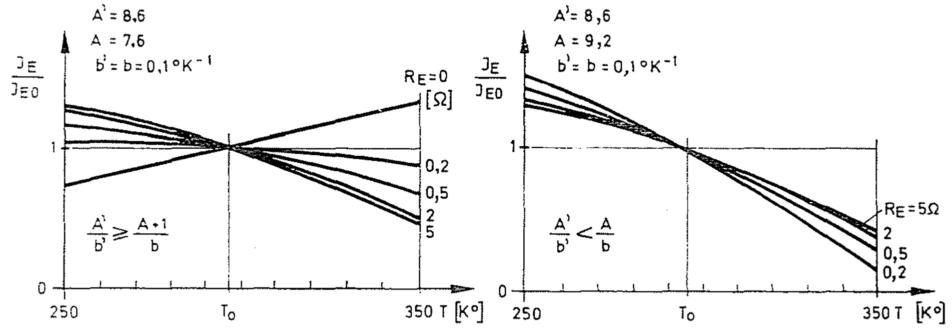
The examination of the function $I_E(T)$ obtained for the current of the output transistors, with the parameters encountered in practice, resulted in the following overall properties:

a) With increasing values of resistance R_E the function $I_E(T)$ always flattens to a curve monotonously decreasing with temperature.

$$\lim_{R_E \to \infty} \left. \frac{\partial I_E}{\partial T} \right|_{T=T_0} = K I_{EO} \quad \text{where} \quad K < 0 .$$

b) For low resistance values R_E the slope of the function can be zero or positive if factors A' and A, dependent on the ratios of operating point currents to saturation currents (I'_E: I'_{SO} and $I_E : I_{SO}$) are related as:

$$\frac{A'}{b'} \geq \frac{A+1}{b} . \tag{25}$$



$J_{E0} = 0{,}1\text{A}$; $\gamma = 0{,}29$; $\Theta_{ja} = 8{,}2 \text{K°/W}$

Fig. 7. Characteristic temperature-dependence of the current of the power transistors for various ratios of parameters A to A'

The above properties are shown in Fig. 7. The analysis of the function $I_E(T)$ as well as the computation and the plottings of the presented curves were carried out by means of a Hewlett-Packard 9100B desk calculator. To check the theory and the correctness of the simplifying neglections, measurements were carried out with the circuit illustrated in Fig. 8. The curves representing the emitter current and the ambient temperature computed from data delivered by the circuit are shown in Fig. 9. The results demonstrate that the calculations satisfy the usual accuracy requirements in the range of room temperature ± 40 °C.

If condition (25) is fulfilled, there is a possibility of getting the function $I_E(T)$ with horizontal tangent at room temperature. The relevant factor δ can be obtained by derivating (23):

$$\left. \frac{\partial I_E}{\partial T} \right|_{T=T_0} = 0 \quad \text{if} \quad \delta = \delta_T ,$$

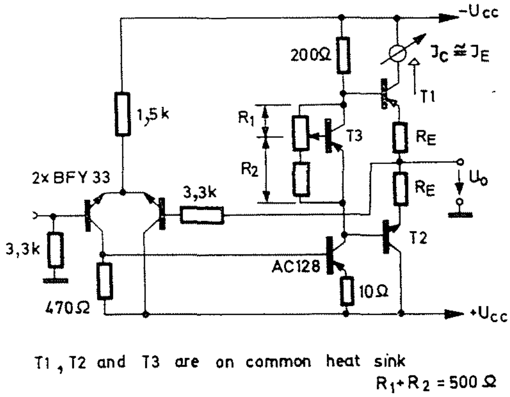


Fig. 8. Circuit diagram for control measurements

where

$$\delta_T = 2\,\frac{b(T_0+2I_{EO}\,U_{CE}\,\Theta_{ja})-A-1}{b'(T_0+2I_{EO}\,U_{CE}\,\Theta_{ja}\,\gamma)-A'}\,. \tag{26}$$

In designing the circuit, it is reasonable to determine the δ_T value from Eq. (26), using the given starting data and relationships (5), (6), (20) and (22). The value of δ_T obtained this way permits to determine the optimum resistance R_E from Eq. (24). If the circuit is built with this resistance, the current I_{EO} prescribed for temperature T_0 can be adjusted accurately by minor changes of resistances R_1 and R_2 (also a potentiometer can be used). This method can eliminate the error of the approximation in (13).

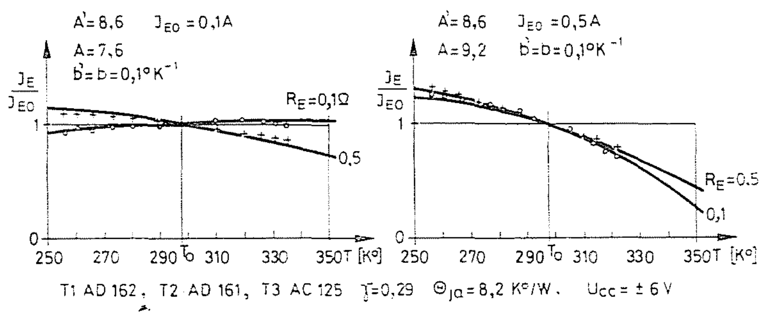


Fig. 9. Computed and measured temperature dependence in the circuit of Fig. 8 for two different values of the current I_{EO}

Condition (25) relating to the quantities A and A' cannot always be fulfilled if both the output transistors and the compensating transistor are Ge transistors. In such cases Si transistors have to be chosen as compensating transistor, since then A' considerably increases due to its small saturation current. In such cases, however, the temperature-independent biasing will be obtained with a higher R_E, likely to impair the efficiency of the circuit.

Table 1 contains the data important for the temperature-independent biasing of the output stage shown in Fig. 8, realized at two different working points. For an operating current $I_{EO} = 0.5$ A (column 2) the task could only be solved with a Si compensating transistor because of the facts mentioned. Table 1 indicates the ambient temperature range examined and the recorded maximum change of current.

Table I

		1.	2.
Characteristics of the power transistors	type	AD 161	AD 162
	I_{EO} [A]	0.1	0.5
	A	7.6	9.2
Cooling data	Θ_{ja} [K/W]	8,2	
	γ	0.29	
Characteristics of the compensating transistor	type	AC 125	BSY 58
	I' [mA]	30	
	A'	8.6	26
Circuit parameters	R_E [Ω]	0.13	1.2
	δ	1.03	1.15
	R_1 [Ω]	245	225
	R_2 [Ω]	255	275
	U_{cc} [V]	± 6	
Ambient temp. [°C]		-23 — $+60$	-23 — $+45$
The measured rel. current change $\frac{\Delta I_E}{I_{EO}}$ max		-3%	-3%

5. Realizability of an operating point independent of the dissipated power

The previous statements are valid for constant dissipation. In control with changing amplitude, the power dissipated by the transistors changes as well, involving the change of the junction temperature. The effect can only be computed with an input signal fulfilling the following condition: The signal frequency is high enough so that the thermal inertia of the transistor cannot prevent its junction temperature T_j from following the instantaneous value of the power dissipation. Thereby the two transistors have nearly identical junction temperatures that change only with the change of the average value of the input signal.

The relation between dissipated power and output level is determined by the class of the operating point. The relationship between dissipated power and output level, for sinusoidal signal amplification, is shown in Fig. 10.

Relationship (23) can be used also for the determination of the dependence of current I_E on the dissipation. In the relationship the change of P_d can be simulated by proportionally changing the voltage U_{CE} $(P_d \simeq I_E U_{CE})$.

The current I_E is independent of P_d if

$$\frac{\partial I_E}{\partial U_{CE}} = 0 .$$

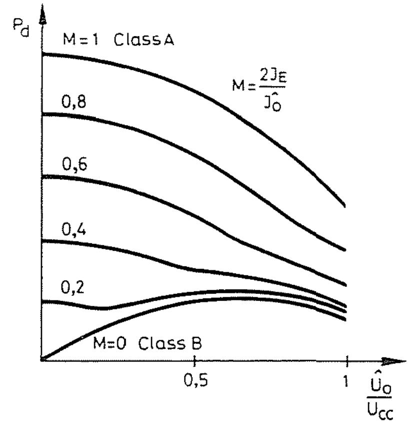


Fig. 10 Variation of the dissipated power at different operating points vs. output level (sinusoidal signal)

Differentiation of relationship (23) shows that the above condition is fulfilled if:

$$\delta = \frac{2}{\gamma} \; \frac{b(T_0 + 2I_{EO}\, U_{CE}\, \Theta_{ja}) - A - 1}{b'(T_0 + 2I_{EO}\, U_{CE}\, \Theta_{ja}\, \gamma) - A'} = \delta_P . \tag{27}$$

A close relation is seen to exist between δ_T for a dissipation-independent I_E setting and δ_P for an I_E independent of ambient temperature

$$\delta_T = \frac{\delta_P}{\gamma} . \tag{28}$$

An I_E independent of both effects can only be realized if $\gamma = 1$. Namely for $\gamma \neq 1$, the changes of temperatures T and T_j are sensed differently by the compensating transistor and the output transistors.

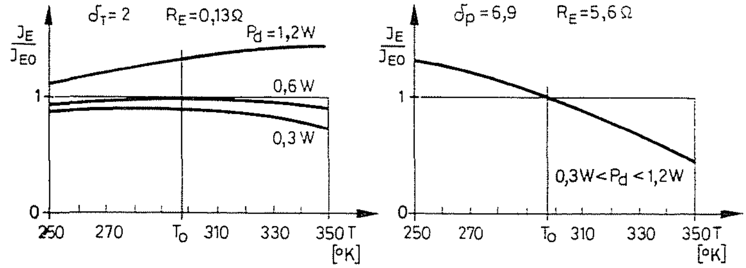


Fig. 11. Dependence of the operating point current on ambient temperature and dissipation

For a circuit constructed of discrete elements $\gamma < 1$, hence the realization of the dissipation-independent I_E requires a greater resistance R_E than that necessary for a temperature-independent I_E. (The ratio of resistances R_E is greater than $1/\gamma$.) Fig. 11 shows the temperature-dependence of the same circuit $I_E = f(T)$ with two different operating points.

6. Conclusion

If the output stage is biased by means of a compensating transistor, the operating point current of the power transistors can be kept at a constant value in a wide range of temperature. A current independent also of dissipation can, however, be realized only by means of a compensating transistor placed in common house (or in a common chip) with the power transistors.

With power amplifiers built of discrete components it is favourable to choose an operating point of class AB, parameter $M = 0.2$, for in this case the dissipation hardly changes with the output signal. Thus, it is sufficient to ensure the temperature-independence of the current of the operating point.

Summary

The operating point current of power transistors is much affected by the ambient temperature and by dissipation. The presented analysis aims at establishing the conditions for the realization of an operating point current independent of the effects mentioned. On the basis of the results, it is possible to determine the optimum resistance R_E of the complementary symmetry output stage and to design the biasing circuit.

References

1. The Application of Linear Microcircuits. SGS, London—Milan—Paris, 1968.
2. CHERY, E. M., HOOPER, D. E.: Amplifying Devices and Low-pass Amplifier Design. Wiley, New York—London—Sydney, 1968.
3. TELKES, B.: Tranzisztoros egyenfeszültség-erősítők a méréstechnikában és az automatikában. Műszaki Könyvkiadó. Budapest, 1968.
4. TIETZE, U. SCHENK, CH.: Halbleiter-Schaltungstechnik. Springer, Berlin—Heidelberg—New York, 1969.
5. VARGA, S.: Operating point stability of the output transistors of power amplifiers. Mérés és Automatika **8** 300 (1971). (in Hungarian)

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