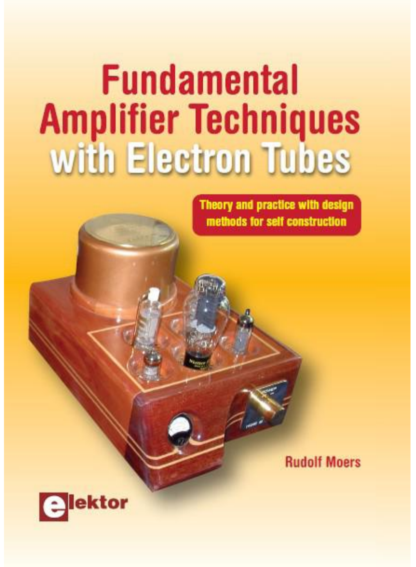
The Ultra Linear Power Amplifier

An adventure between triode and pentode



by Rudolf Moers

Who am I

Born in 1955 in Veldhoven and now living in Eindhoven in the Netherlands.

Education:	Primary	Technical School	→	electrical engineering
	Secondary	Technical School	→	electronics
	High	Technical School	→	electronics

Summary of work experience:

Halin	→	Analog video modification (RGB-keying) Analog audio circuits with semi-conductors
Philips Optical Disk Mastering	→	Compact Disk mastering electronics Compact Disk signal processing electronics And a lot more
Philips Medical Systems	→	Diaphragm control of Röntgen camera
Philips Electron Optics	→	Vacuum pump control for electron microscope
Secondary Technical School	→	Teacher electronics, theory and practice
ASML	→	Architecture of electronic hardware Infrastructure of cabling and racks with electronic boards and supplies.

Hobby : electron tube amplifiers and radio's

Contents of this presentation

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1. Introduction and history

David Hafler & Herbert Keroes (not the inventors) published their Ultra Linear story in 1951.

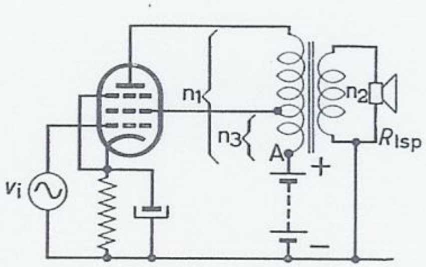
Publishing in 1959 of the Dutch book “Radio Technique part 1” written by A. J. Sietsma of the Philips company.

The Philips company has never published an Ultra Linear story, but A. J. Sietsma made a homework exercise about screen grid negative feedback for students.

Opgave 5

Gegeven:

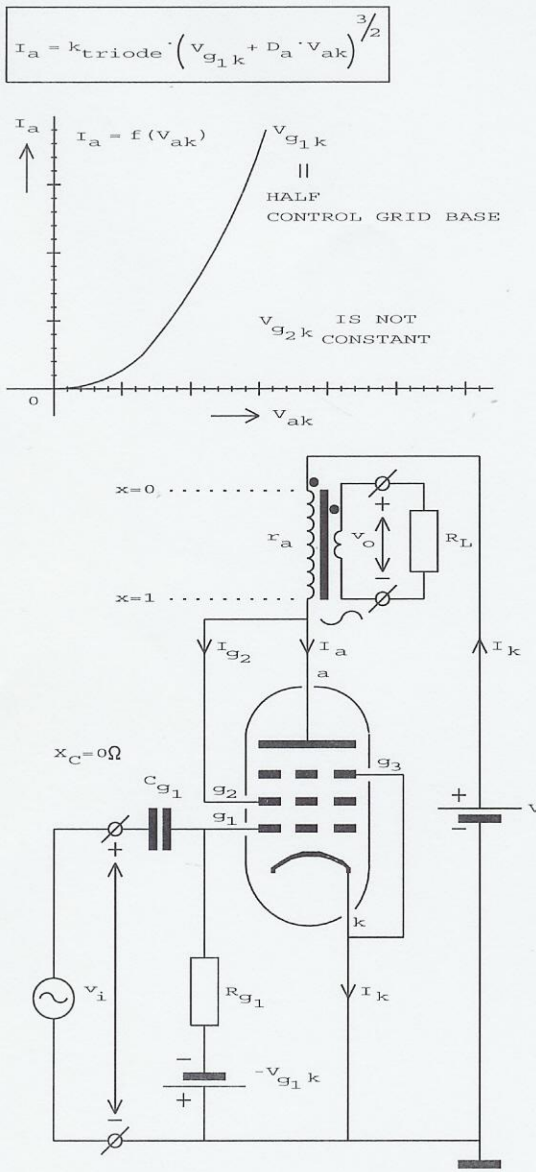
$R_i = 50\ \text{k}\Omega;\ S = 12\frac{1}{2}\ \text{mA/V};$
$\mu_{g2g1} = 15;\ S_2 = 2{,}5\ \text{mA/V};$
$n_1 : n_2 : n_3 = 40 : 1 : 15;\ R_{lsp} = 7{,}5\ \Omega.$



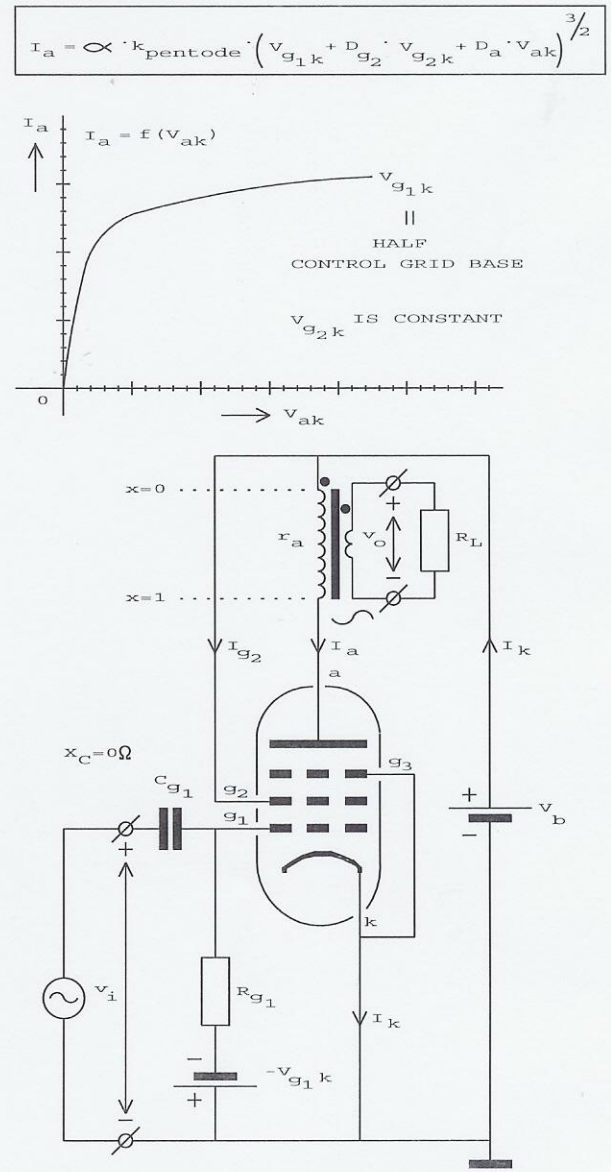
Gevraagd:

1. Bereken $\frac{v_a}{v_i}$ indien men de eindtrap niet tegenkoppelt (d.w.z. g_2 ligt dan aan punt A).
2. Bereken $\frac{v_a}{v_i}$ indien men de eindtrap wel tegenkoppelt (zoals in het gegeven schema).
3. Welke soort tegenkoppeling treedt er hier op?

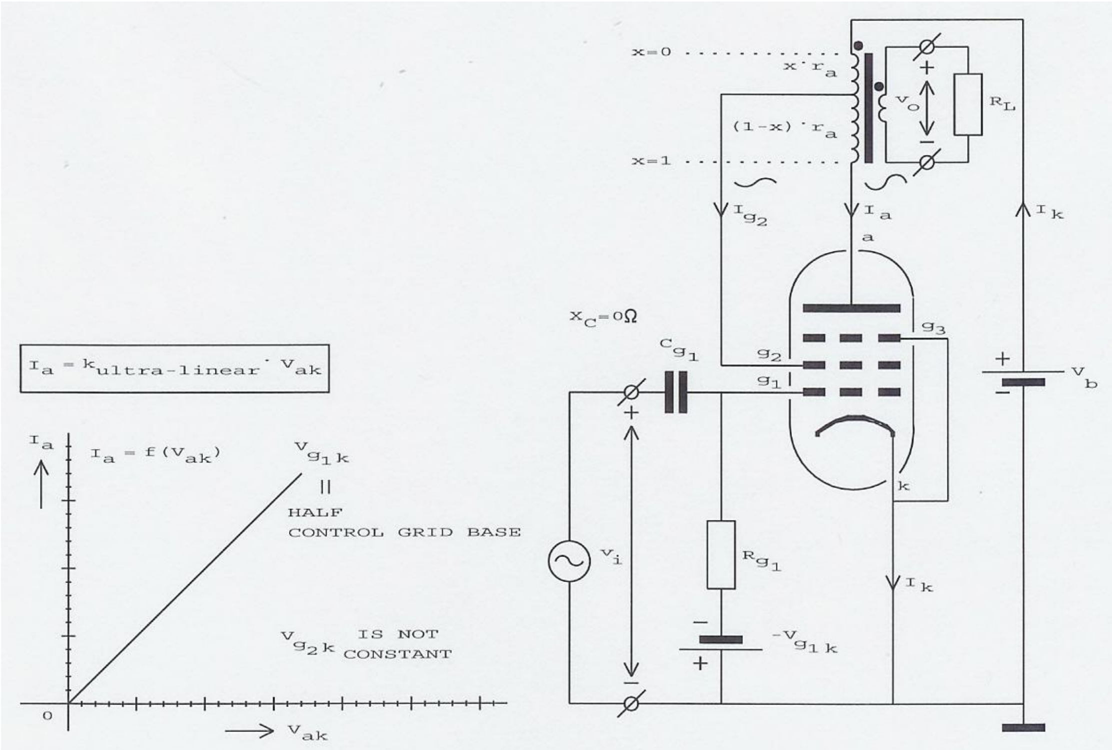
Rudolf Moers solved this homework exercise about negative feedback in 2006 with his own formulae which gave the same results as A. J. Sietsma.



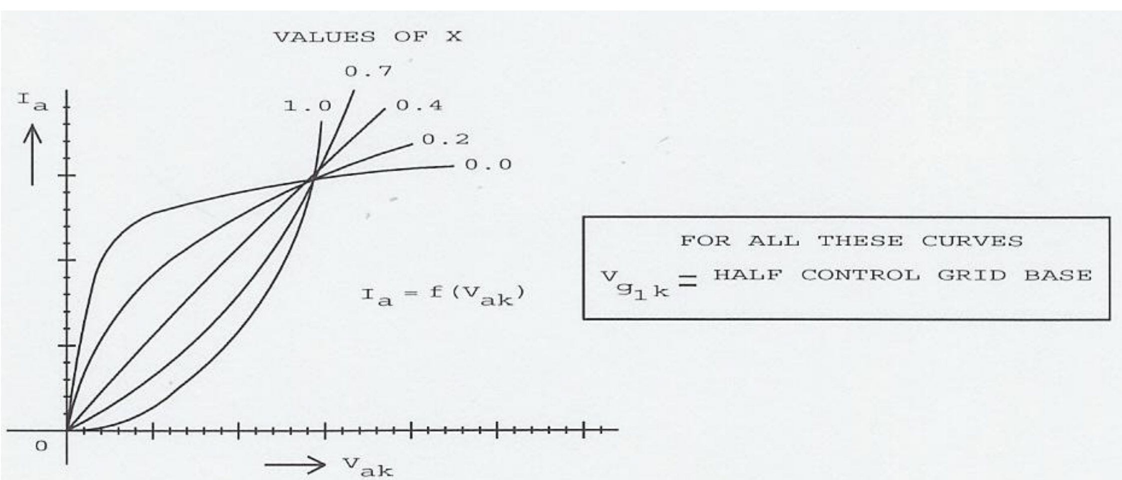
PENTODE AS TRIODE



PENTODE AS PENTODE



PENTODE AS ULTRA-LINEAR



Screen grid tap of the primary transformer winding : x

$$x \approx \frac{v_{g2,k}}{v_{ak}} \rightarrow x = \frac{v_{g2,k}}{v_{ak}}$$

$$v_{g2,k} = x \cdot v_{ak}$$

$$0.0 \leq x \leq 1.0$$

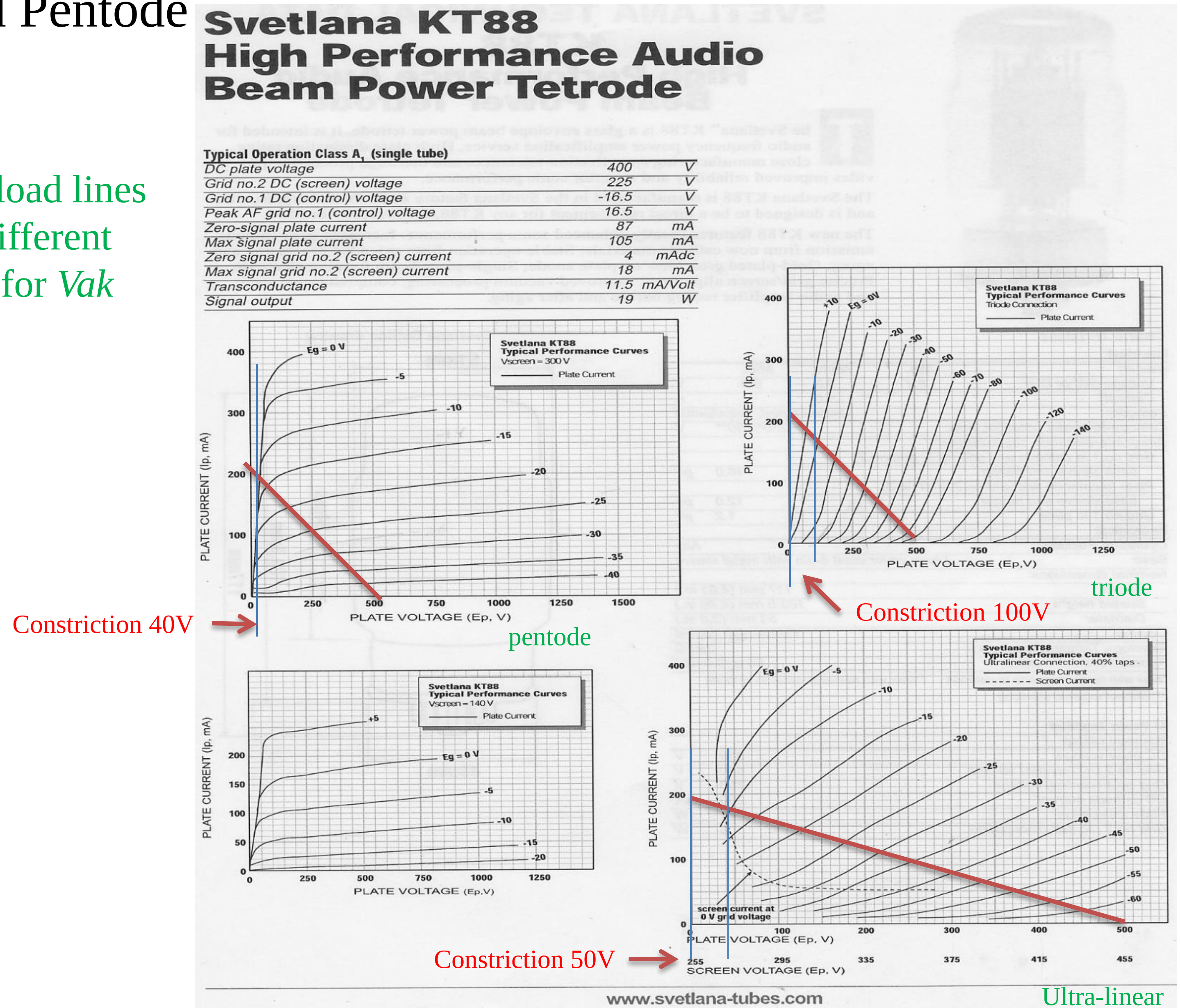
$x = 0$: pentode

$0 < x < 1$: ultra-linear

$x = 1$: triode

2. Comparison of the static characteristic for Triode, Ultra Linear and Pentode

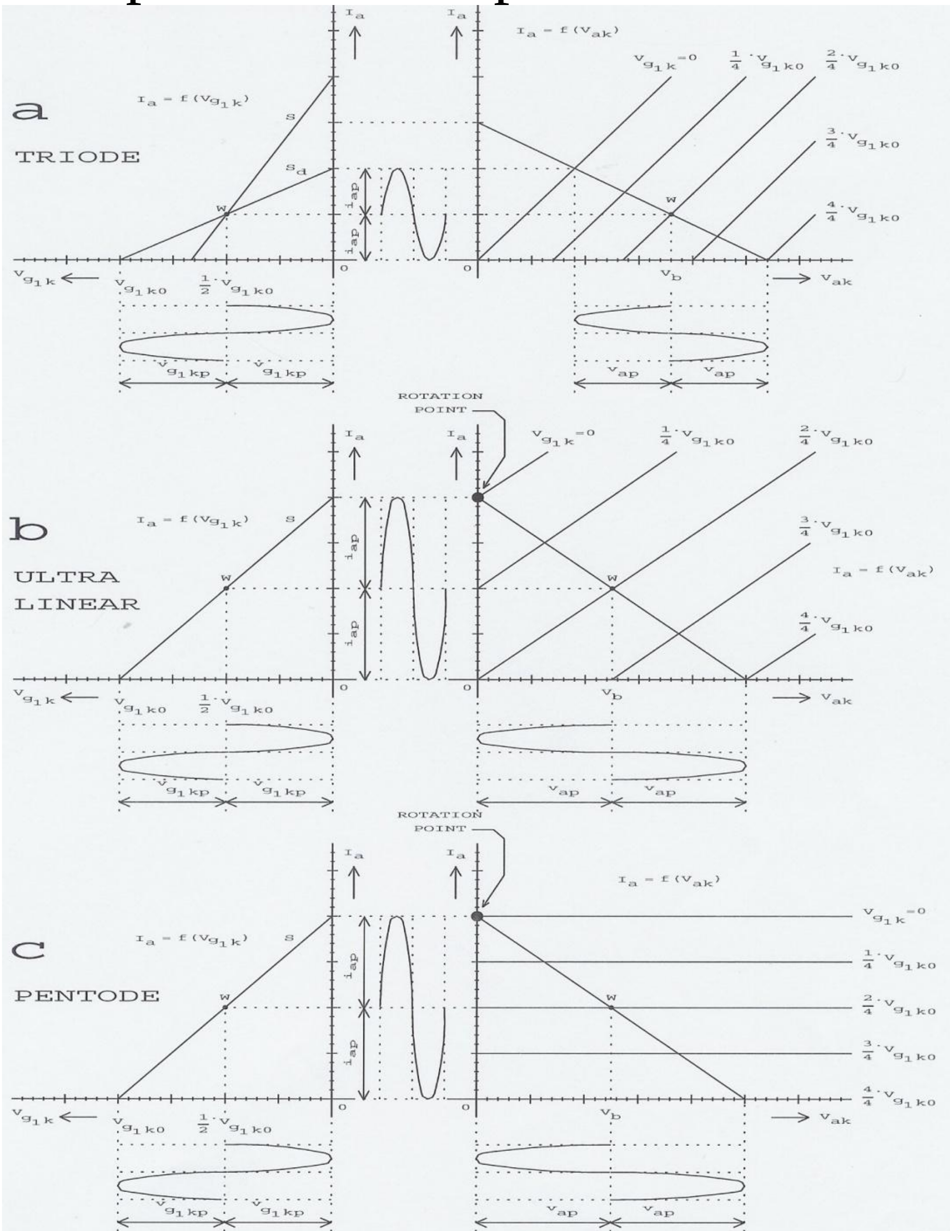
Same load lines with different scales for *Vak*



Svetlana KT88 High Performance Audio Beam Power Tetrode

Typical Operation Class A, (single tube)		
DC plate voltage	400	V
Grid no.2 DC (screen) voltage	225	V
Grid no.1 DC (control) voltage	-16.5	V
Peak AF grid no.1 (control) voltage	16.5	V
Zero-signal plate current	87	mA
Max signal plate current	105	mA
Zero signal grid no.2 (screen) current	4	mAdc
Max signal grid no.2 (screen) current	18	mA
Transconductance	11.5	mA/Volt
Signal output	19	W

3. Comparison of the powers for Triode, Ultra Linear and Pentode in theory.



$V_{ap,triode} \ll V_{ap,ultralinear}$

$V_{ap,triode} \ll V_{ap,pentode}$

$I_{ap,triode} \ll I_{ap,ultralinear}$

$I_{ap,triode} \ll I_{ap,pentode}$

$V_{a,pentode} = V_{a,ultralinear}$

$I_{a,pentode} = I_{a,ultralinear}$

By this:

$P_{ap,triode} \ll P_{ap,ultralinear}$

$P_{ap,triode} \ll P_{ap,pentode}$

$P_{a,pentode} = P_{a,ultralinear}$

Comparison of the powers for Triode, Ultra Linear and Pentode in practice.

In Menno's first book some design examples are shown which use with jumpers to configure the circuit into triode, ultra-linear and pentode.

Power results:

2x EL34 with transformer VDV6040PP: p_{triode} = 13W, $p_{ultralinear}$ = 33W and $p_{pentode}$ = 40W
4x EL34 with transformer VDV3070PP: p_{triode} = 30W, $p_{ultralinear}$ = 70W and $p_{pentode}$ = 80W

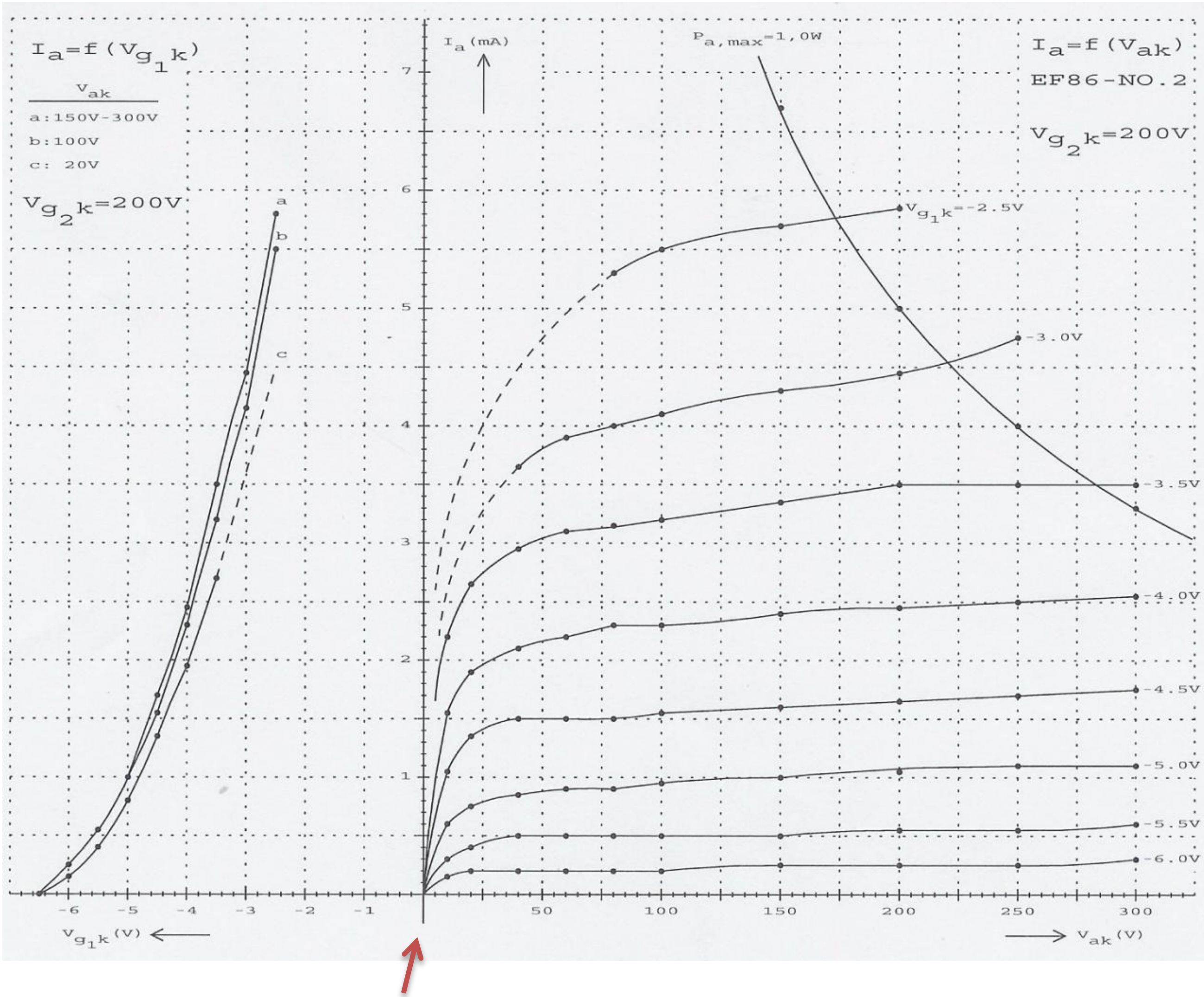
p_{triode} = 13 W ← 20 W → $p_{ultralinear}$ = 33 W versus $p_{ultralinear}$ = 33 W ← 7 W → $p_{pentode}$ = 40 W
p_{triode} = 30 W ← 40 W → $p_{ultralinear}$ = 70 W versus $p_{ultralinear}$ = 70 W ←10 W → $p_{pentode}$ = 80 W

Reason : $v_{ap,triode} << v_{ap,ultralinear} < v_{ap,pentode}$

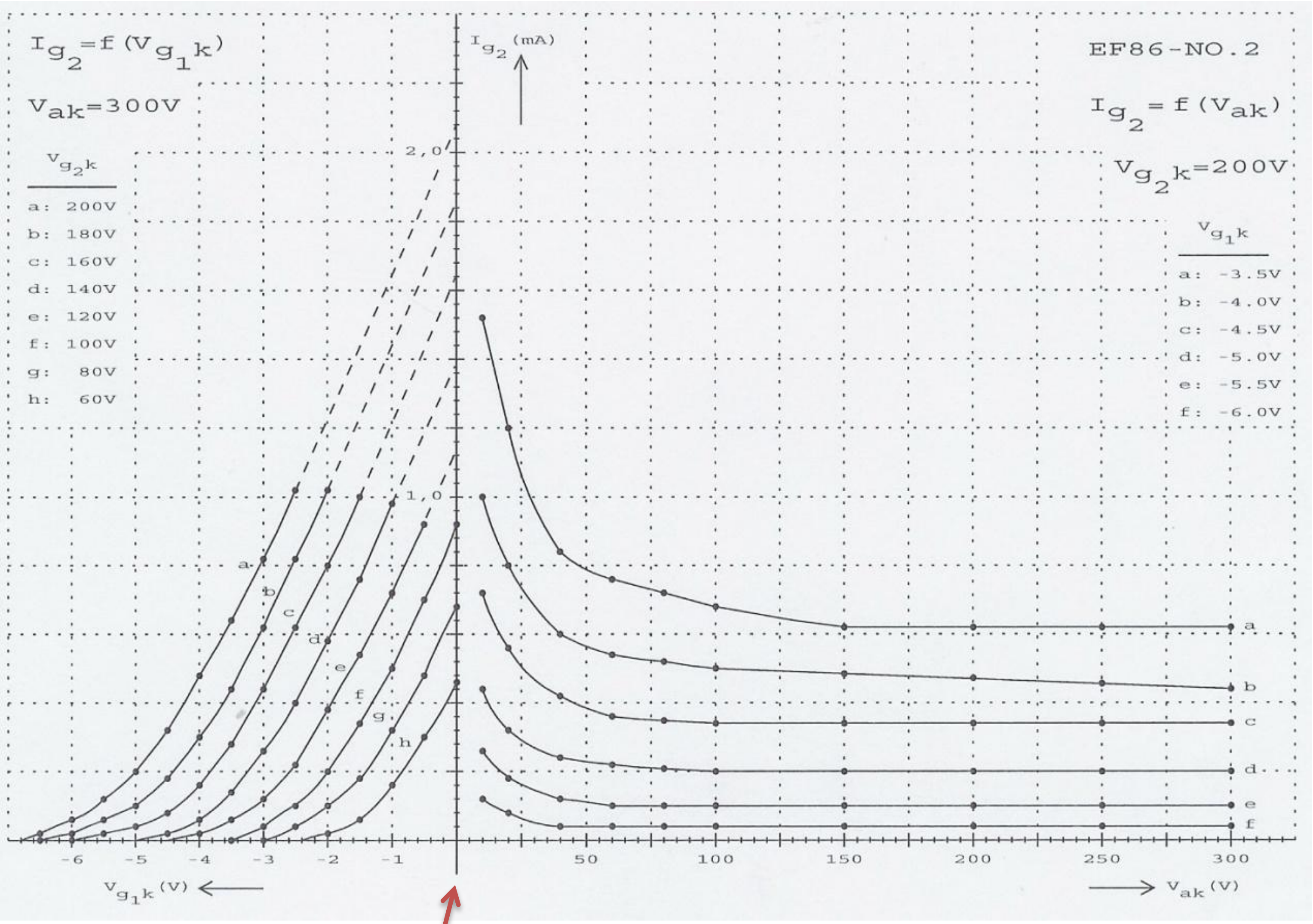
The constriction of the $v_{g1,k}$ -curves in the anode characteristic $I_a = f(V_{ak})$ near the I_a –axis is slightly more with ultra linear than with a pentode.

4. Network analyses of the Ultra Linear Amplifier

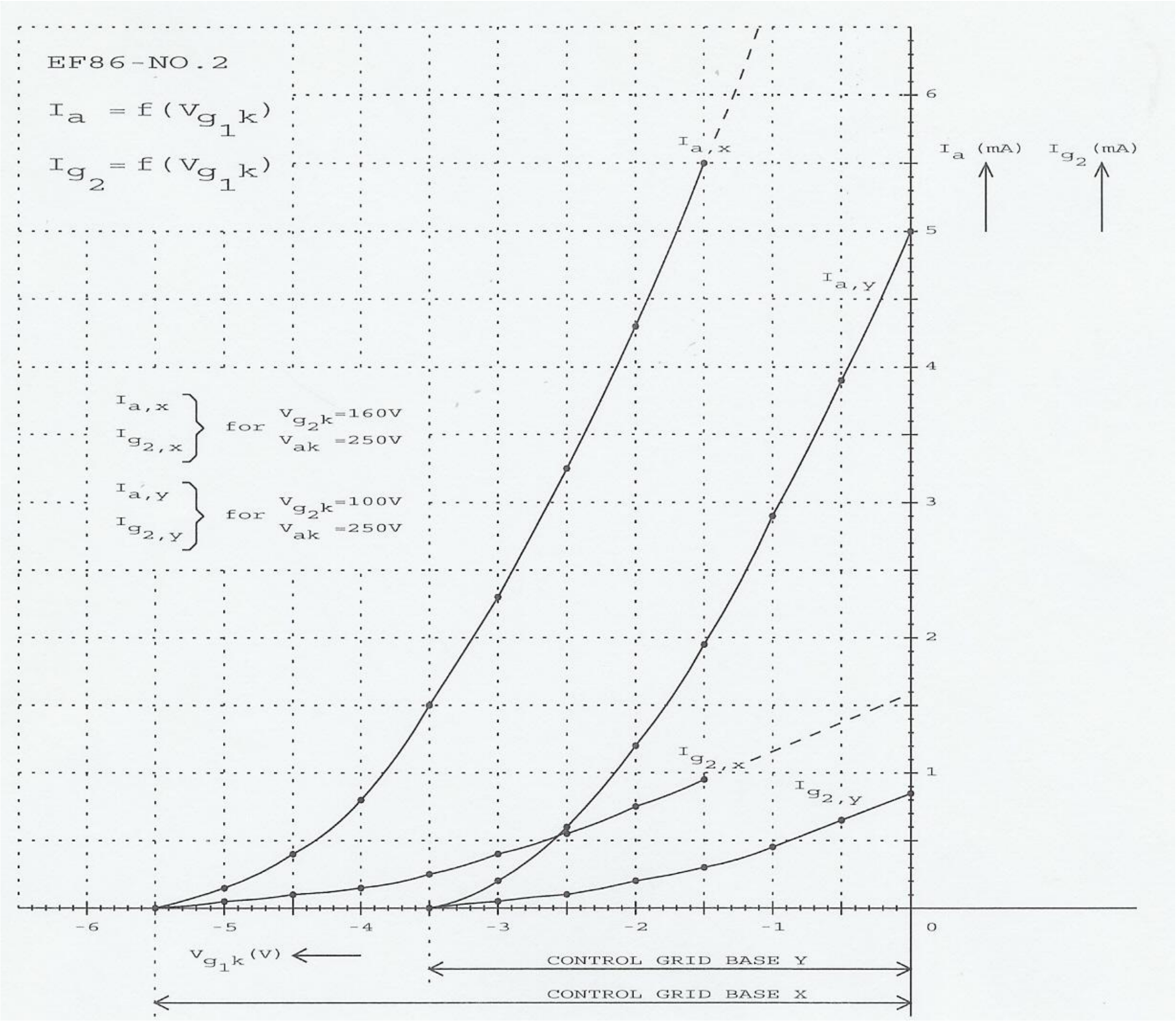
4.a. Repetition of the pentode characteristics



Anode current



Screen grid current


EF86-NO.2
I_a = f(V_g1k)
I_g2 = f(V_g1k)
I_a,x
I_a,y
I_g2,x
I_g2,y
I_a (mA)
I_g2 (mA)
I_a,x } for V_g2k=160V
I_g2,x } V_ak =250V
I_a,y } for V_g2k=100V
I_g2,y } V_ak =250V
V_g1k (V)
CONTROL GRID BASE Y
CONTROL GRID BASE X
-6 -5 -4 -3 -2 -1 0
1 2 3 4 5 6

4.b. Repetition of the pentode quantities

Anode steepness is also called mutual conductance g_m.

Definition of <u>anode steepness</u> : $S = \frac{\Delta I_a}{\Delta V_{g1,k}}$ with constant V_{ak} and $V_{g2,k}$

For small signals : $S = \frac{i_a}{v_{g1,k}}$ with constant V_{ak} and $V_{g2,k}$

Definition of <u>screen grid steepness</u> : $S_2 = \frac{\Delta I_{g2}}{\Delta V_{g1,k}}$ with constant V_{ak} and $V_{g2,k}$

For small signals : $S_2 = \frac{i_{g2}}{v_{g1,k}}$ with constant V_{ak} and $V_{g2,k}$

Definition of <u>anode amplification factor</u> : $$\mu = \left|\frac{\Delta V_{ak}}{\Delta V_{g1,k}}\right|$$ with constant I_a and $V_{g2,k}$

For small signals : $$\mu = \left|\frac{v_{ak}}{v_{g1,k}}\right|$$ with constant I_a and $V_{g2,k}$

Definition of <u>screen grid amplification factor</u> : $$\mu_{g2,g1} = \left|\frac{\Delta V_{g2,k}}{\Delta V_{g1,k}}\right|$$ with constant I_{g2} and V_{ak}

For small signals : $$\mu_{g2,g1} = \left|\frac{v_{g2,k}}{v_{g1,k}}\right|$$ with constant I_{g2} and V_{ak}

Anode penetration factor : $D_a = \mu^{-1} = 1/\mu$ (Anode Durchgriff)

Screen grid penetration factor : $D_{g2} = \mu_{g2,g1}^{-1} = 1/\mu_{g2,g1}$ (Screen grid Durchgriff)

Definition of anode AC internal resistance : $r_i = \dfrac{\Delta V_{ak}}{\Delta I_a}$ with constant $V_{g1,k}$ and $V_{g2,k}$

For small signals : $r_i = \dfrac{v_{ak}}{i_a}$ with constant $V_{g1,k}$ and $V_{g2,k}$

Definition of screen grid AC internal resistance : $r_{i2} = \dfrac{\Delta V_{g2,k}}{\Delta I_{g2}}$ with constant $V_{g1,k}$ and V_{ak}

For small signals : $r_{i2} = \dfrac{v_{g2,k}}{i_{g2}}$ with constant $V_{g1,k}$ and V_{ak}

Barkhausen's anode formula : $\mu = S \cdot r_i$

Barkhausen's screen grid formula : $\mu_{g2,g1} = S_2 \cdot r_{i2}$

$$\boldsymbol{\mu_{pentode\ \ as\ \ triode} \approx \mu_{g2,g1}}$$

At the anode:

Anode AC <u>internal</u> resistance: r_i (or plate resistance)

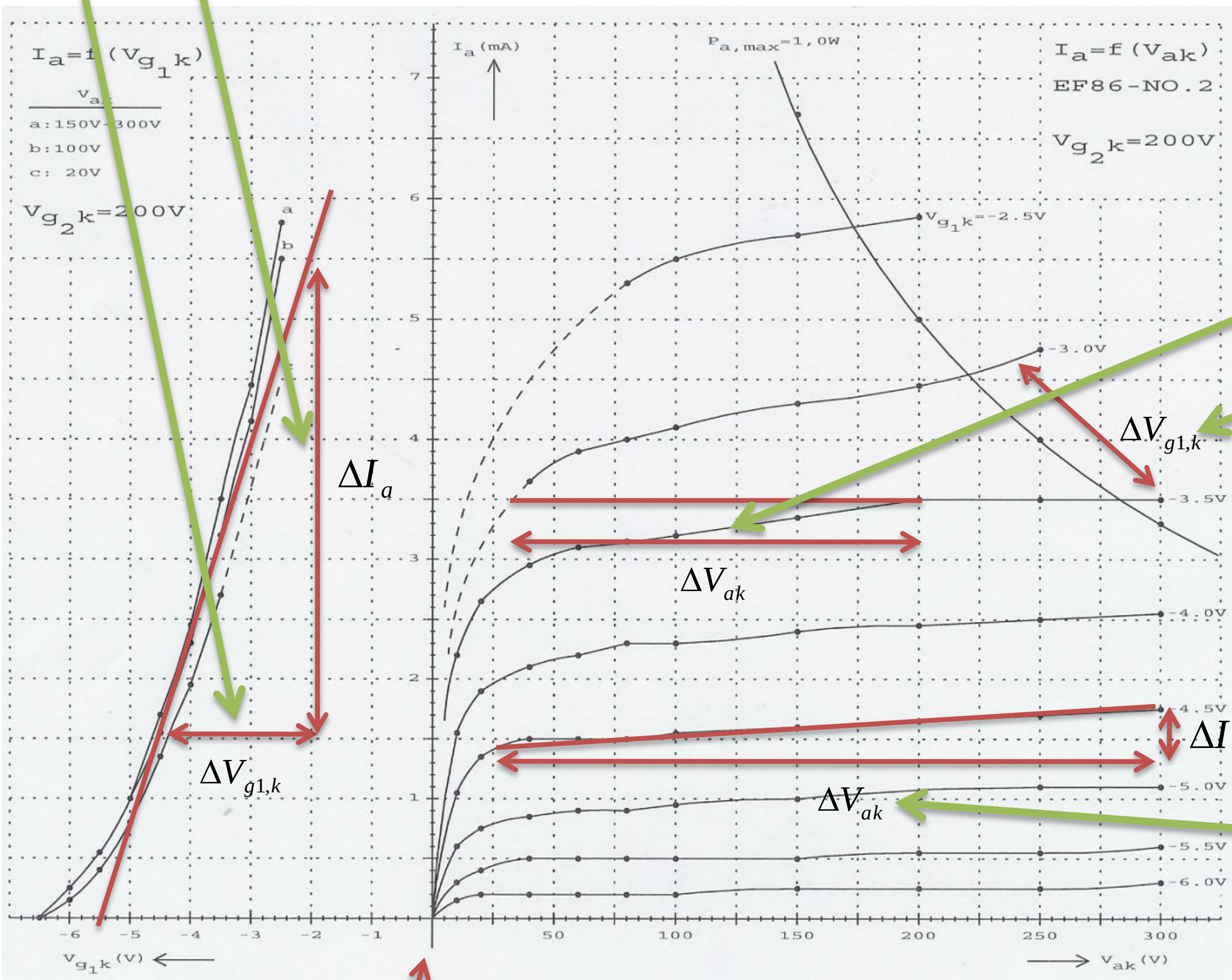
Anode AC <u>external</u> resistance: r_a (external load at the anode)

Screen grid tap of the primary transformer winding : x

$$S = \frac{\Delta I_a}{\Delta V_{g1,k}}$$

$$\mu = \frac{\Delta V_{ak}}{\Delta V_{g1,k}}$$

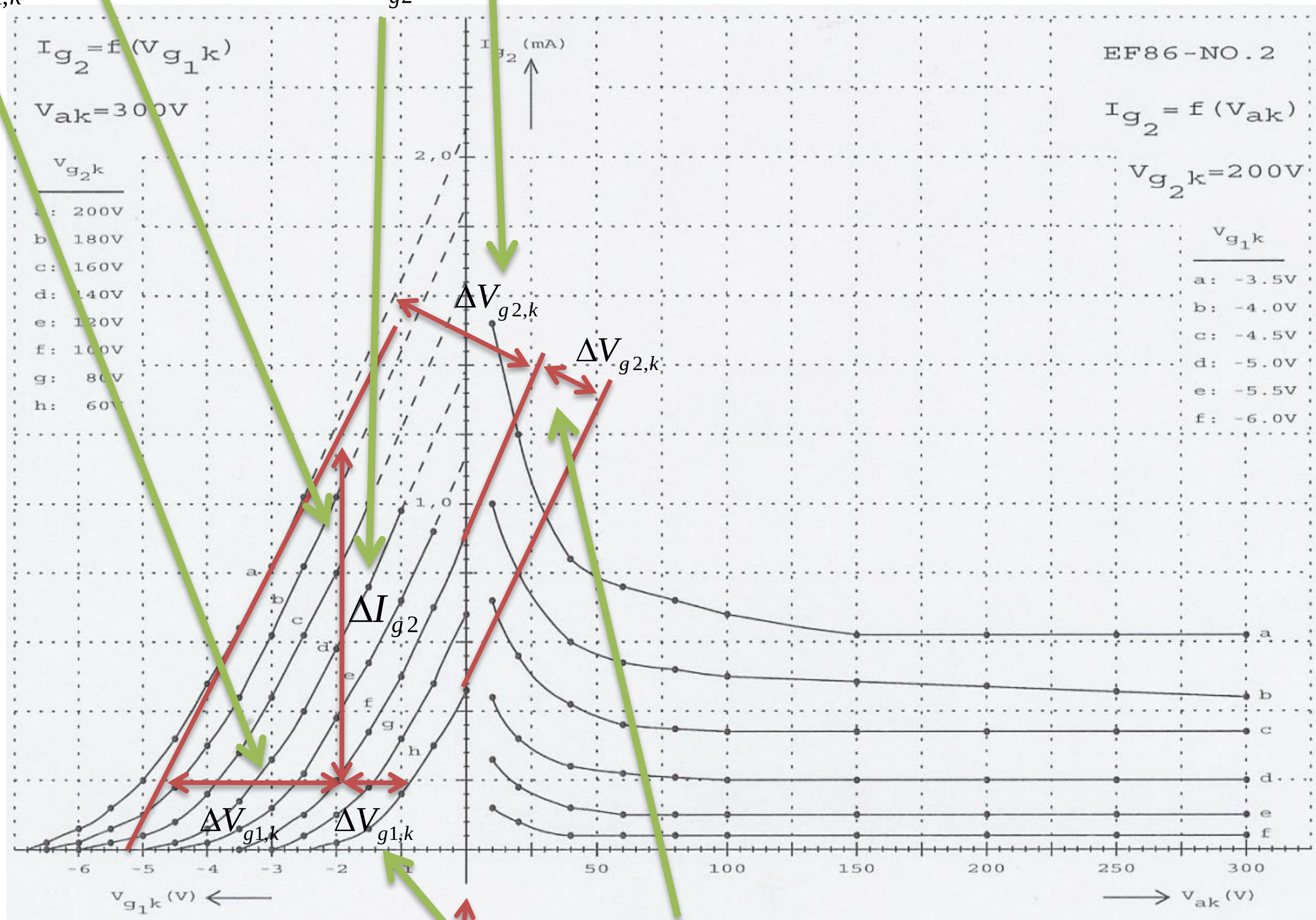
$$r_i = \frac{\Delta V_{ak}}{\Delta I_a}$$



Anode current

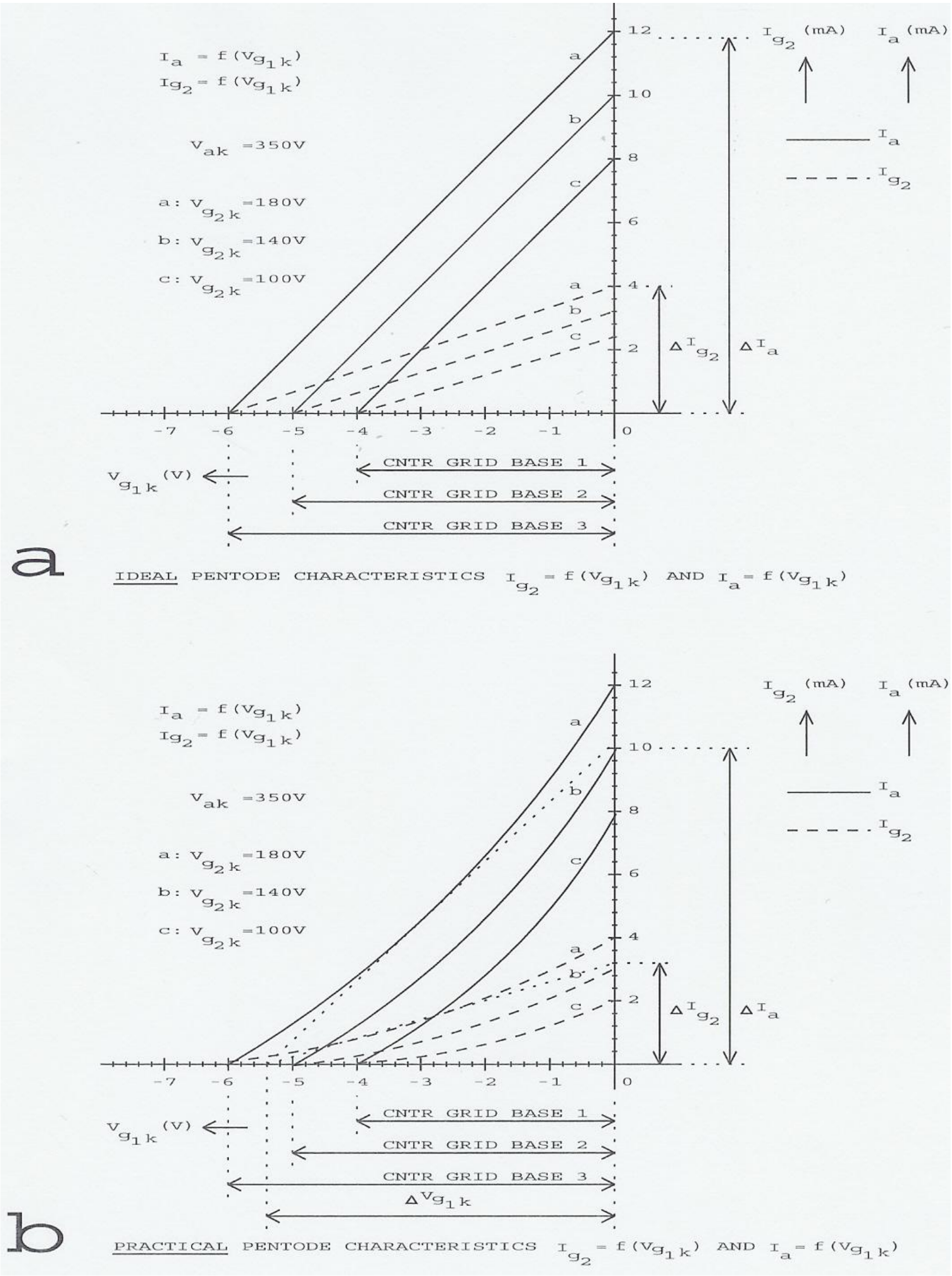
$$S_2 = \frac{\Delta I_{g2}}{\Delta V_{g1,k}}$$

$$r_{i2} = \frac{\Delta V_{g2,k}}{\Delta I_{g2}}$$



$$\mu_{g2,g1} = \frac{\Delta V_{g2,k}}{\Delta V_{g1,k}}$$

Screen grid current



$$S = \frac{\Delta I_a}{\Delta V_{g1,k}}$$

$$S_2 = \frac{\Delta I_{g2}}{\Delta V_{g1,k}}$$

$$\Delta V_{g1,k \ for \ S} = \Delta V_{g1,k \ for \ S2}$$

$$\Delta V_{g1,k} = \frac{\Delta I_a}{S} = \frac{\Delta I_{g2}}{S_2}$$

$$I_{g2} = \frac{S_2}{S} \cdot I_a$$

$$i_{g2} = \frac{S_2}{S} \cdot i_a$$

4.c. Current and Voltage Source equivalent circuits for the Pentode

For triodes:

According to the definitions, AC voltage $v_{g1,k}$ causes anode current : $i_{a1} = S \cdot v_{g1,k}$
According to the definitions, AC voltage v_{ak} causes anode current : $i_{a2} = v_{ak} / r_i$

Superposititon of i_{a1} and i_{a2} gives : $i_a = S \cdot v_{g1,k} + \frac{v_{ak}}{r_i}$ apply Barkhausen's $\mu = S \cdot r_i$

The triode equation : $i_a = S \cdot \left(v_{g1,k} + \frac{v_{ak}}{\mu} \right)$

For pentodes:

Factor $\frac{v_{ak}}{\mu}$ contributes to the anode current slightly because μ is large

see anode steepness characteristic $I_a = f\,(V_{g1,k})$.

Factor $\frac{v_{g2,k}}{\mu_{g2,g1}}$ contributes significantly to the anode current because $\mu_{g2,g1}$

is small, see screen grid steepness characteristic $I_{g2} = f\,(V_{g1,k})$.

The pentode equation : $i_a = S \cdot \left(v_{g1,k} + \frac{v_{g2,k}}{\mu_{g2,g1}} + \frac{v_{ak}}{\mu} \right)$

The pentode equation : $i_a = S \cdot \left(v_{g1,k} + \frac{v_{g2,k}}{\mu_{g2,g1}} + \frac{v_{ak}}{\mu} \right)$

Equal control grid base for anode current and screen grid current : $i_{g2} = \frac{S_2}{S} \cdot i_a$

Apply this in the pentode equation : $i_{g2} = S_2 \cdot \left(v_{g1,k} + \frac{v_{g2,k}}{\mu_{g2,g1}} + \frac{v_{ak}}{\mu} \right)$

After some mathematical magic tricks we get the current source and voltage source models.

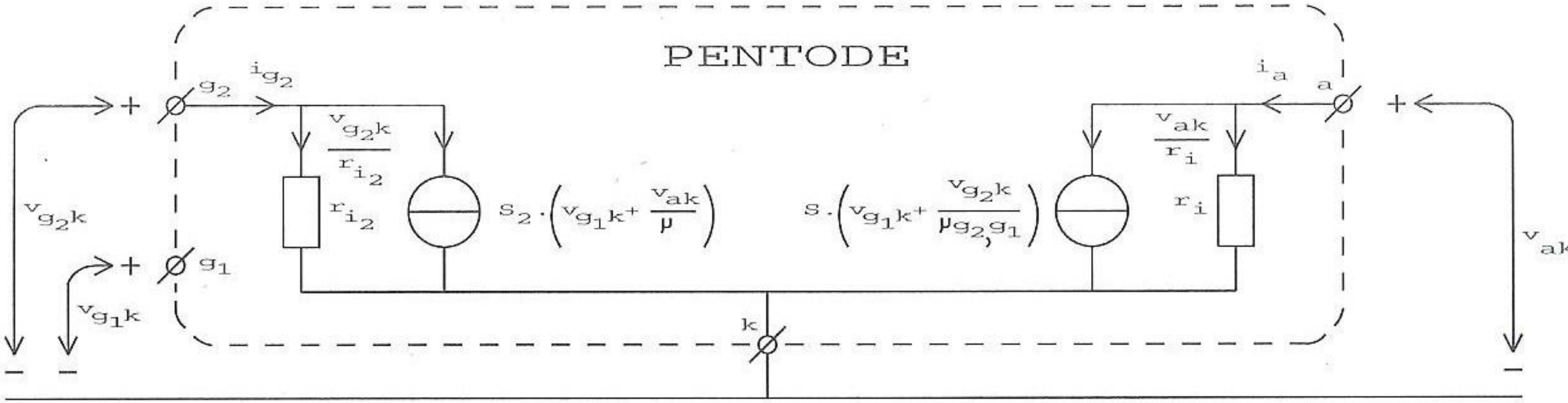
Anode current source : $i_a = S \cdot \left(v_{g1,k} + \frac{v_{g2,k}}{\mu_{g2,g1}} \right) + \frac{v_{ak}}{r_i}$

Screen grid current source : $i_{g2} = S_2 \cdot \left(v_{g1,k} + \frac{v_{ak}}{\mu} \right) + \frac{v_{g2,k}}{r_{i2}}$

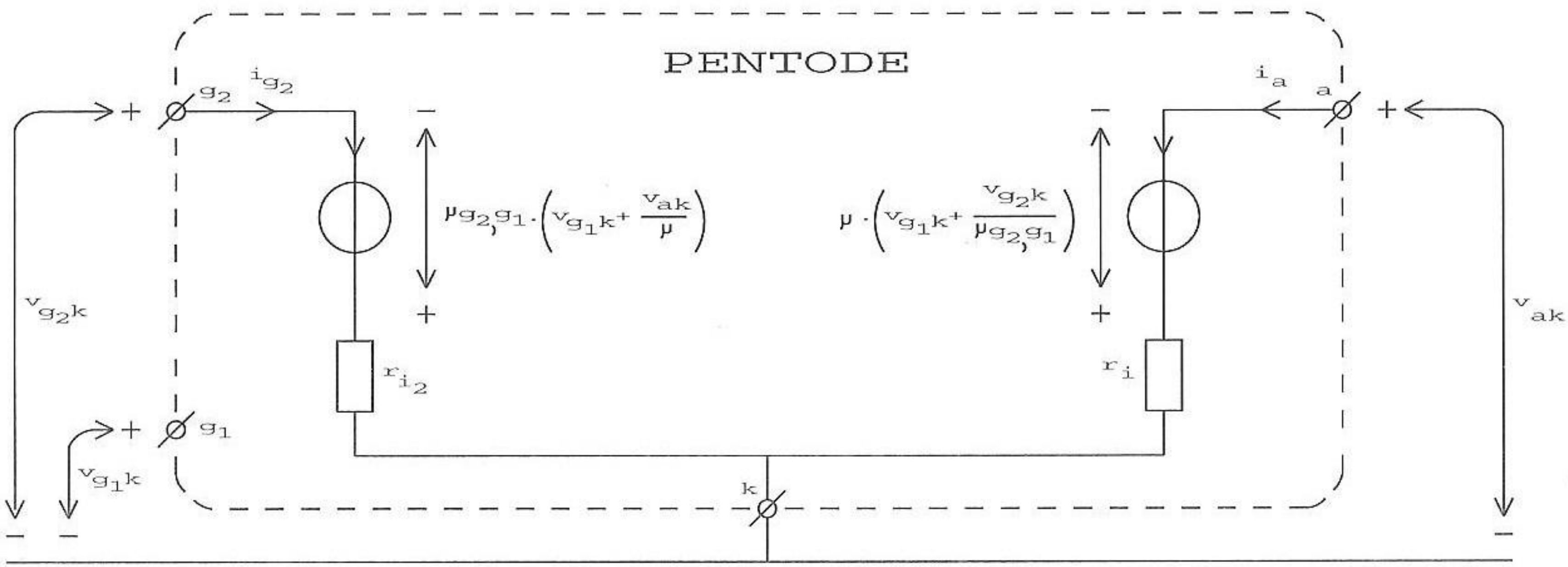
Anode voltage source : $i_a \cdot r_i = \mu \cdot \left(v_{g1,k} + \frac{v_{g2,k}}{\mu_{g2,g1}} \right) + v_{ak}$

Screen grid voltage source : $i_{g2} \cdot r_{i2} = \mu_{g2,g1} \cdot \left(v_{g1,k} + \frac{v_{ak}}{\mu} \right) + v_{g2,k}$

Do not try to remember these terrible formulae, in de next sheet they are understandable.

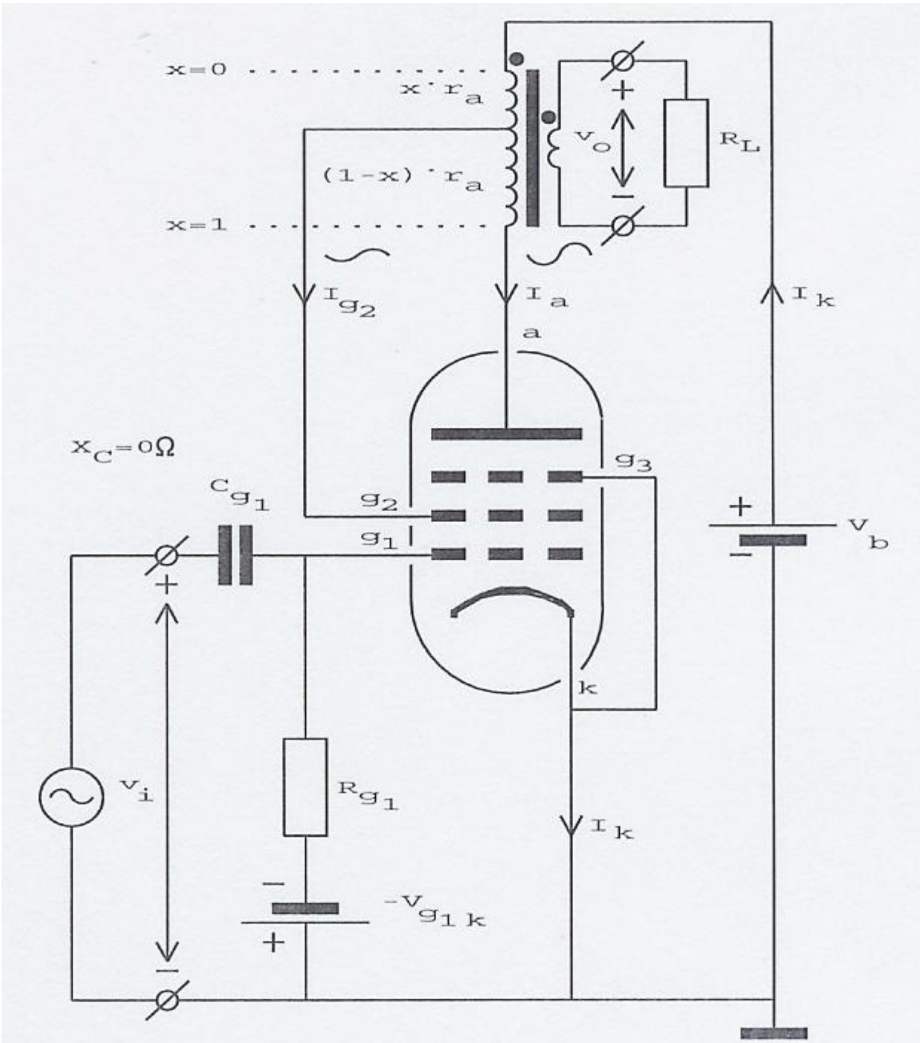


CURRENT SOURCE EQUIVALENT NETWORK



VOLTAGE SOURCE EQUIVALENT NETWORK

4.d. Current source and Voltage Source equivalent circuits applied to Ultra Linear



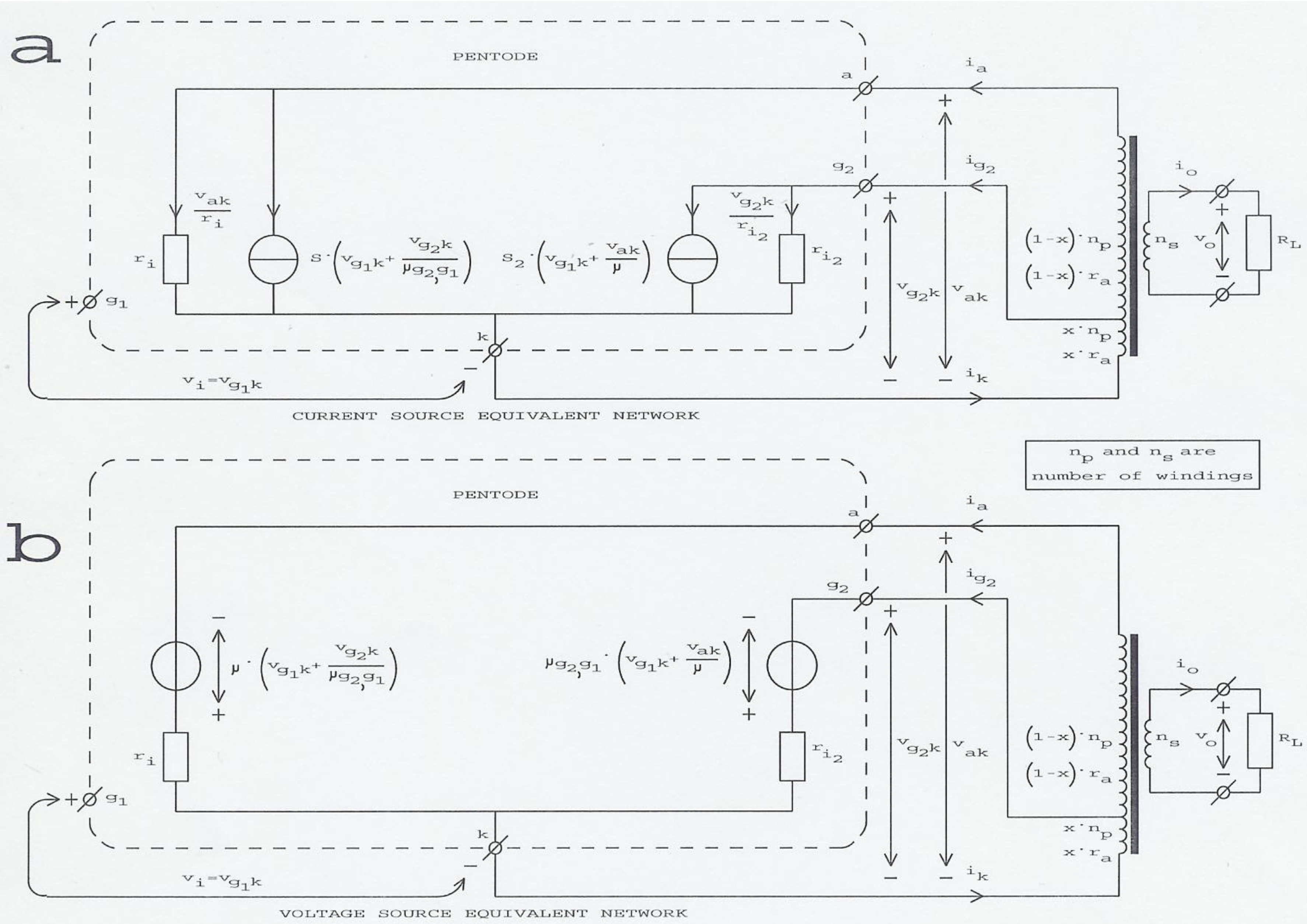
$$x \approx \frac{v_{g2,k}}{v_{ak}} \rightarrow x = \frac{v_{g2,k}}{v_{ak}}$$

$$v_{g2,k} = x \cdot v_{ak}$$

$$0.0 \leq x \leq 1.0$$

TARGET:

$A = v_o / v_i = f(x)$ and $r_{out} = f(x)$



a
PENTODE
a
i_a
g_2
i_{g_2}
i_o
$\frac{v_{ak}}{r_i}$
$\frac{v_{g_2k}}{r_{i_2}}$
r_i
$S \cdot \left(v_{g_1k} + \frac{v_{g_2k}}{\mu_{g_2,g_1}}\right)$
$S_2 \cdot \left(v_{g_1k} + \frac{v_{ak}}{\mu}\right)$
r_{i_2}
v_{g_2k}
v_{ak}
$(1-x) \cdot n_p$
$(1-x) \cdot r_a$
n_s
v_o
R_L
g_1
k
$x \cdot n_p$
$x \cdot r_a$
i_k
$v_i = v_{g_1k}$
CURRENT SOURCE EQUIVALENT NETWORK
n_p and n_s are number of windings
b
PENTODE
a
i_a
g_2
i_{g_2}
$\mu \cdot \left(v_{g_1k} + \frac{v_{g_2k}}{\mu_{g_2,g_1}}\right)$
$\mu_{g_2,g_1} \cdot \left(v_{g_1k} + \frac{v_{ak}}{\mu}\right)$
i_o
r_i
r_{i_2}
v_{g_2k}
v_{ak}
$(1-x) \cdot n_p$
$(1-x) \cdot r_a$
n_s
v_o
R_L
g_1
k
$x \cdot n_p$
$x \cdot r_a$
i_k
$v_i = v_{g_1k}$
VOLTAGE SOURCE EQUIVALENT NETWORK

Without formulae we see directly :

i_{g2} flows through part x of the primary winding → partly contribution to power

i_a flows through part $(1-x)+x$ of the primary winding → full contribution to power

With formulae derivation from the equivalent circuits we achieve :

Anode voltage : $$v_{ak} = v_{g2,k} - i_a \cdot (1-x) \cdot r_a = -i_k \cdot x \cdot r_a - i_a \cdot (1-x) \cdot r_a$$

$v_{g2,k} = -(i_a + i_{g2}) \cdot x \cdot r_a$ and is Kirchhoff's first law $i_k = i_a + i_{g2}$ for AC

Total AC current : $$\frac{v_{ak}}{r_a} = -(i_a + x \cdot i_{g2}) = -i_{total}$$

The total AC current i_{total} is <u>not the same</u> as cathode AC current i_k.

With the art of magic formula tricks …….

The pentode equation :
$$i_a = S \cdot \left(v_{g1,k} + \frac{v_{g2,k}}{\mu_{g2,g1}} + \frac{v_{ak}}{\mu} \right)$$

$$v_{g2,k} = x \cdot v_{ak}$$

$$i_{g2} = \frac{S_2}{S} \cdot i_a$$

$$\frac{v_{ak}}{r_a} = -\left(i_a + x \cdot i_{g2}\right) = -i_{total}$$

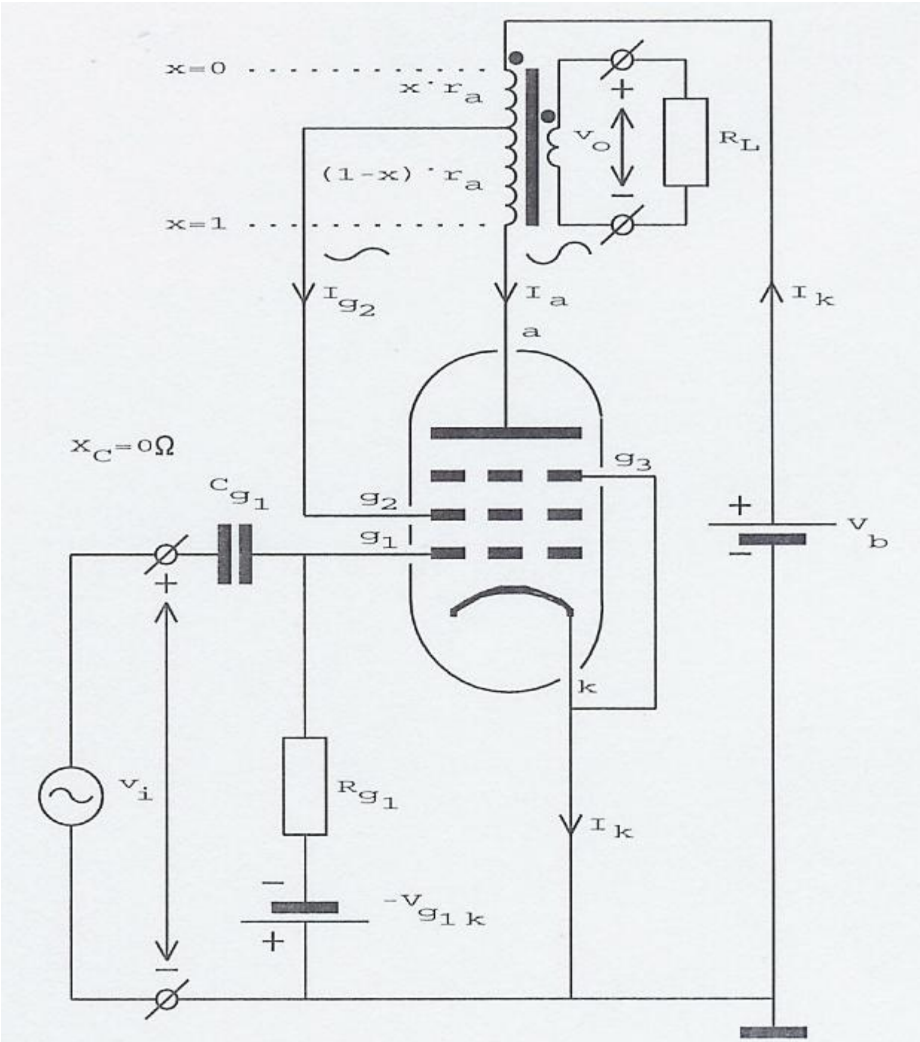
$$i_{total} = \left(1 + x \cdot \frac{S_2}{S}\right) \cdot S \cdot \left(v_{g1,k} + \frac{x \cdot v_{ak}}{\mu_{g2,g1}} + \frac{v_{ak}}{\mu} \right)$$

$$v_{ak} = -i_{total} \cdot r_a$$

…………. we achieve at the anode:

$$A_a = \frac{v_{ak}}{v_{g1,k}} = -\frac{\left(S + x \cdot S_2\right) \cdot r_a}{1 + \left(\frac{x}{\mu_{g2,g1}} + \frac{1}{\mu} \right) \cdot \left(S + x \cdot S_2\right) \cdot r_a}$$

An easy formula derivation in small steps is available.



$$A_a = \frac{v_{ak}}{v_{g1,k}} = -\frac{(S + x\cdot S_2)\cdot r_a}{1+\left(\frac{x}{\mu_{g2,g1}}+\frac{1}{\mu}\right)\cdot(S+x\cdot S_2)\cdot r_a}$$

$$v_o = \frac{n_s}{n_p}\cdot v_{ak} \quad and \quad v_i = v_{g1,k}$$

$$A = \frac{v_o}{v_i} = -\frac{n_s}{n_p}\cdot\frac{(S + x\cdot S_2)\cdot r_a}{1+\left(\frac{x}{\mu_{g2,g1}}+\frac{1}{\mu}\right)\cdot(S+x\cdot S_2)\cdot r_a}$$

AC output resistance : $r_{out} = \left| \dfrac{v_{o,open}}{i_{o,shortcircuit}} \right|$ (Thevenin's theorem)

When we have $v_{o,open}$ then $R_L = \infty$ with $r_a = \left(\dfrac{n_s}{n_p} \right)^2 \cdot R_L = \infty$.

When we have $i_{o,shortcircuit}$ then $R_L = 0$ with $r_a = \left(\dfrac{n_s}{n_p} \right)^2 \cdot R_L = 0$.

Again with the art of magic formula tricks ….

$$r_{out} = \left| \frac{v_{o,open}}{i_{o,shortcircuit}} \right|$$

$$\frac{v_{o,open}}{v_i} = -\frac{n_s}{n_p} \cdot \frac{1}{\left(\dfrac{x}{\mu_{g2,g1}} + \dfrac{1}{\mu} \right)}$$

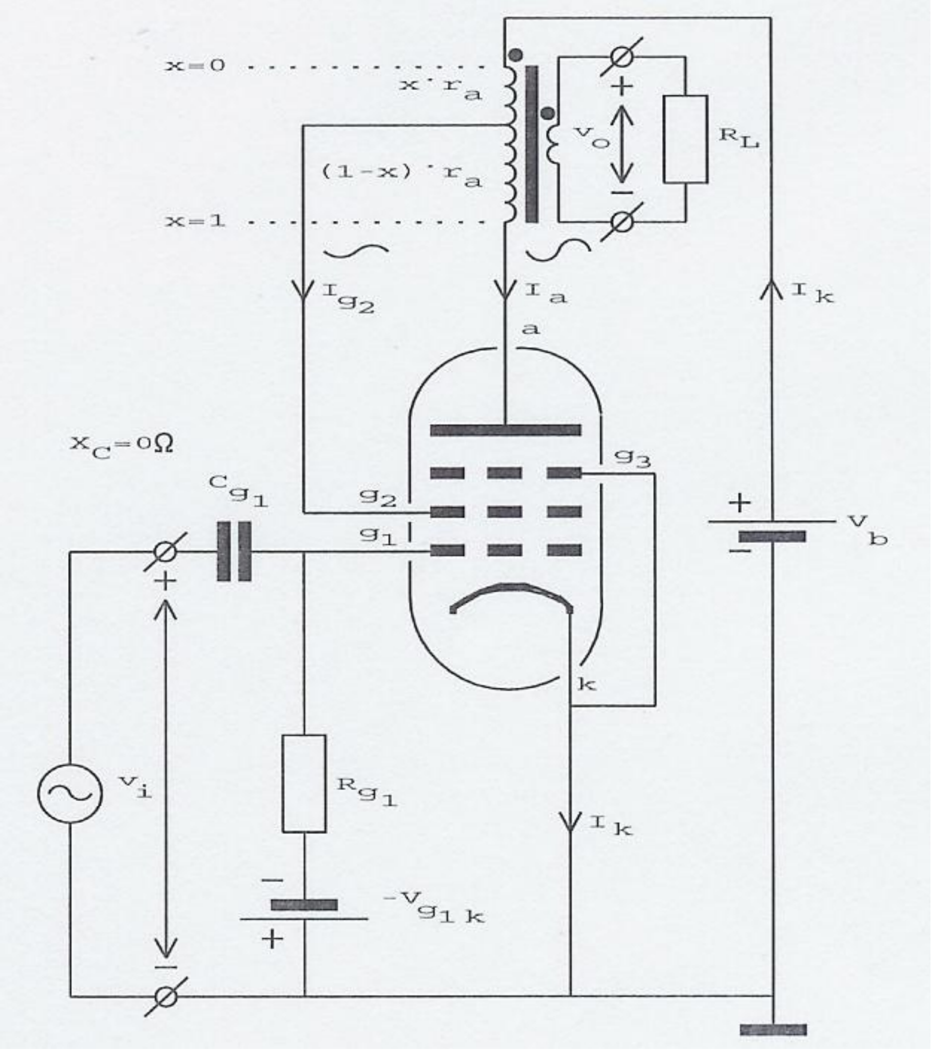
$$i_{o,shortcircuit} = \frac{n_p}{n_s} \cdot \left(1 + x \cdot \frac{S_2}{S} \right) \cdot S \cdot v_i$$

…………. we achieve at the output:

$$r_{out} = \left(\frac{n_s}{n_p} \right)^2 \cdot \frac{1}{(S + x \cdot S_2) \cdot \left(\dfrac{x}{\mu_{g2,g1}} + \dfrac{1}{\mu} \right)}$$

An easy formula derivation in small steps is available.

Summary

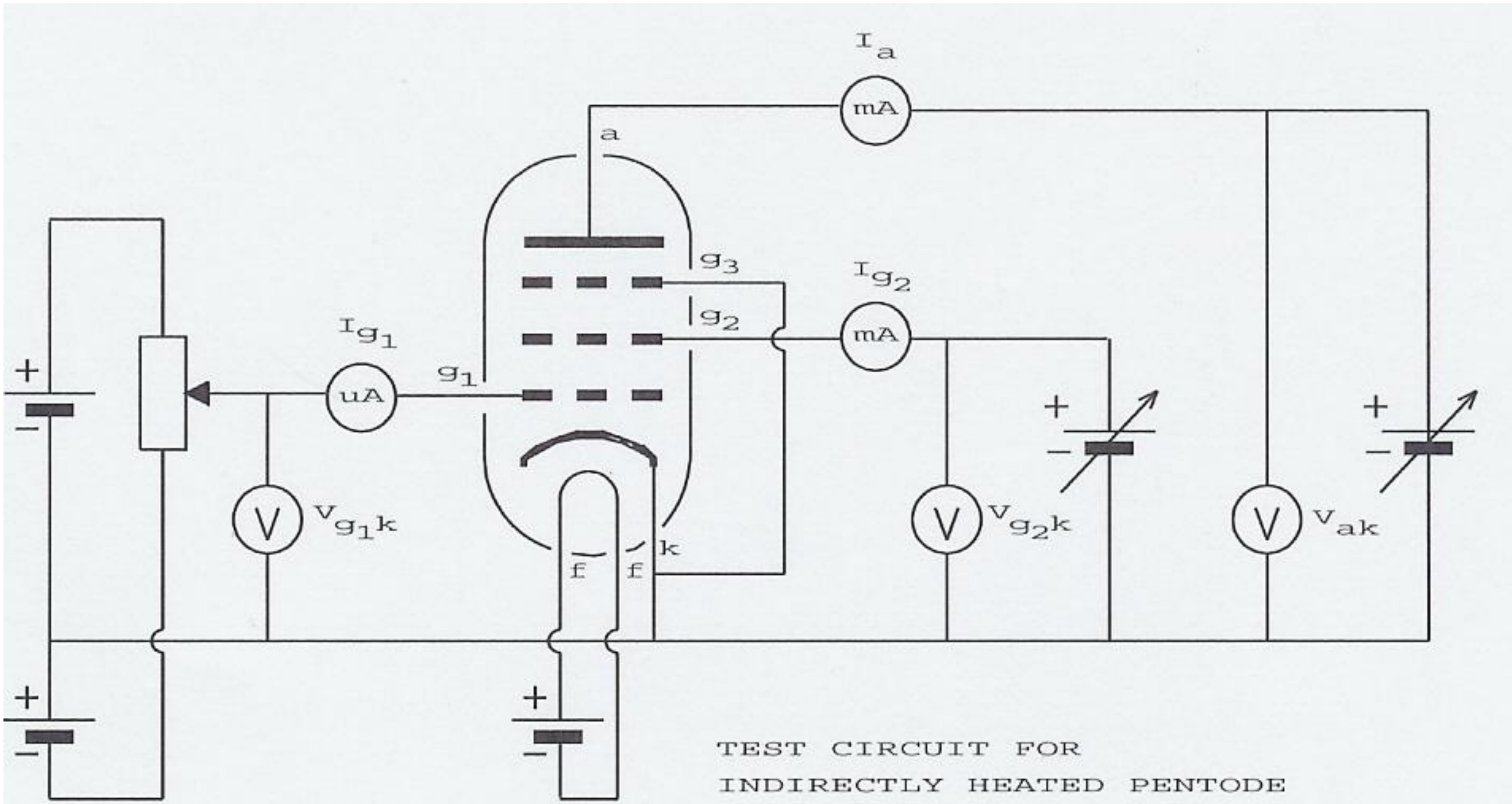


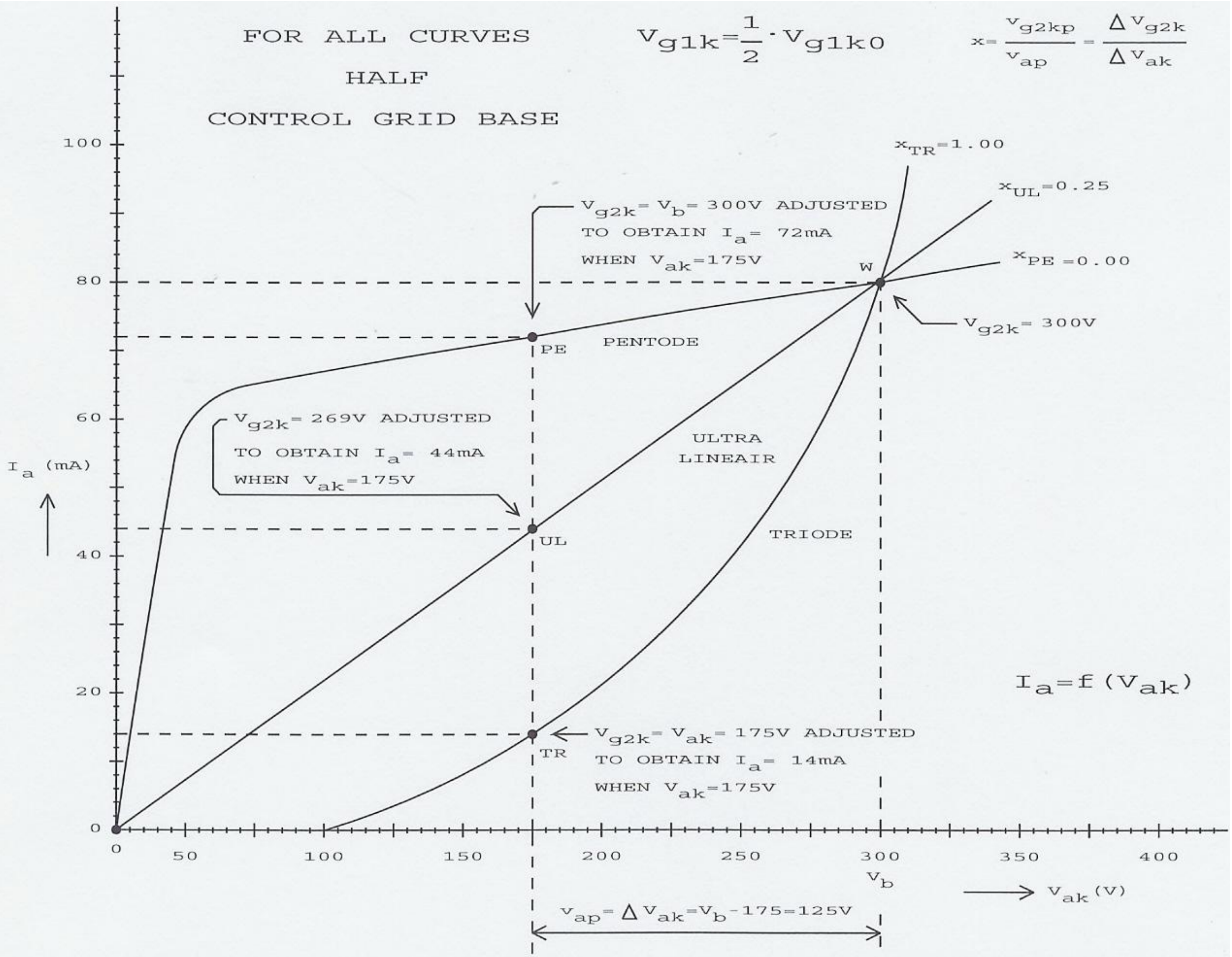
$$A=\frac{v_o}{v_i}=-\frac{n_s}{n_p}\cdot\frac{(S+x\cdot S_2)\cdot r_a}{1+\left(\frac{x}{\mu_{g2,g1}}+\frac{1}{\mu}\right)\cdot(S+x\cdot S_2)\cdot r_a}$$

$$r_{out}=\left(\frac{n_s}{n_p}\right)^2\cdot\frac{1}{(S+x\cdot S_2)\cdot\left(\frac{x}{\mu_{g2,g1}}+\frac{1}{\mu}\right)}$$

x is the variable and the other quantities are almost constant (in theory).

5. Determination of the screen grid tap





<u>IN POINT PE:</u> $v_{g2kp} = \Delta V_{g2k} = V_b - 300 = 0V$ ⟶ $x_{PE} = \frac{v_{g2kp}}{v_{ap}} = \frac{\Delta V_{g2k}}{\Delta V_{ak}} = \frac{0V}{125V} = 0,00$

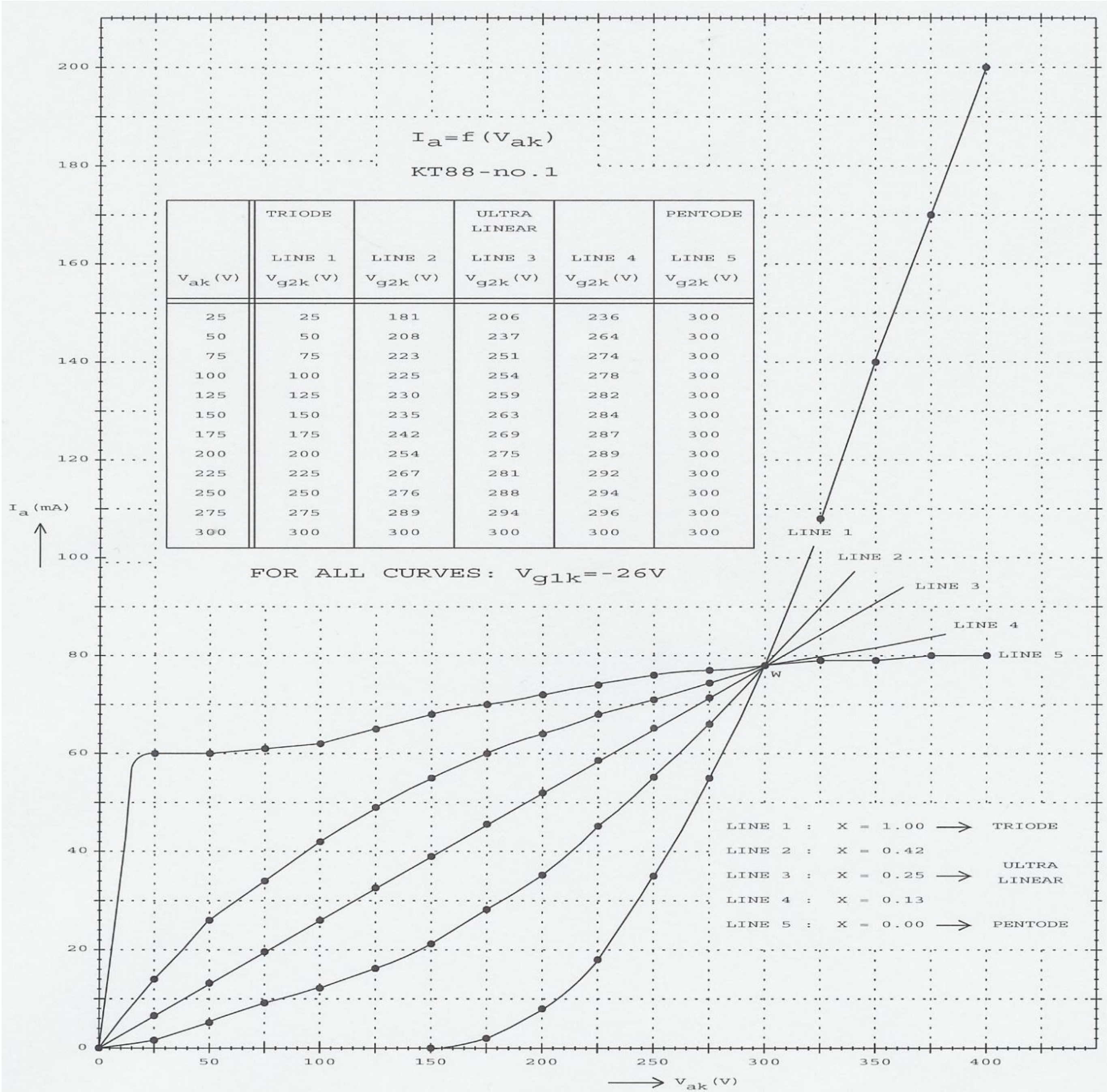
$v_{ap} = \Delta V_{ak} = V_b - 175 = 125V$

<u>IN POINT UL:</u> $v_{g2kp} = \Delta V_{g2k} = V_b - 269 = 31V$ ⟶ $x_{UL} = \frac{v_{g2kp}}{v_{ap}} = \frac{\Delta V_{g2k}}{\Delta V_{ak}} = \frac{31V}{125V} = 0.25$

$v_{ap} = \Delta V_{ak} = V_b - 175 = 125V$

<u>IN POINT TR:</u> $v_{g2kp} = \Delta V_{g2k} = V_b - 175 = 125V$ ⟶ $x_{TR} = \frac{v_{g2kp}}{v_{ap}} = \frac{\Delta V_{g2k}}{\Delta V_{ak}} = \frac{125V}{125V} = 1.00$

$v_{ap} = \Delta V_{ak} = V_b - 175 = 125V$



V_{ak} (V)	TRIODE LINE 1 V_{g2k} (V)	LINE 2 V_{g2k} (V)	ULTRA LINEAR LINE 3 V_{g2k} (V)	LINE 4 V_{g2k} (V)	PENTODE LINE 5 V_{g2k} (V)
25	25	181	206	236	300
50	50	208	237	264	300
75	75	223	251	274	300
100	100	225	254	278	300
125	125	230	259	282	300
150	150	235	263	284	300
175	175	242	269	287	300
200	200	254	275	289	300
225	225	267	281	292	300
250	250	276	288	294	300
275	275	289	294	296	300
300	300	300	300	300	300

Table 1. Measured values of **line 1**						
V_{ak} (V) adjusted	I_a (mA) read on I_a-axis	I_{g2} (mA) measured	$V_{g2,k}$ (V) adjusted to achieve the read I_a	ΔV_{ak} (V) [300V – V_{ak}]	$\Delta V_{g2,k}$ (V) [300V – $V_{g2,k}$]	$x = \frac{\Delta V_{g2,k}}{\Delta V_{ak}}$
0	0	0	0	300	300	1.00
25	0	0	25	275	275	1.00
50	0	0	50	250	250	1.00
75	0	0	75	225	225	1.00
100	0	0	100	200	200	1.00
125	0	0	125	175	175	1.00
150	0	0	150	150	150	1.00
175	2.6	0.1	175	125	125	1.00
200	8.5	0.7	200	100	100	1.00
225	19.2	1.6	225	75	75	1.00
250	35.6	2.9	250	50	50	1.00
275	55	4.6	275	25	25	1.00
300	79	7.0	300	0	0	unknown
325	110	9.2	325	Not further than point W	Not further than point W	Not further than point W
350	140	12.1	350			
375	170	16.5	375			
400	200	21.0	400			

The adjustment of $V_{g2,k}$ happens automatically of course, because the screen grid is connected to the anode. The screen grid primary transformer tap x = 1.00 but that will surprise nobody, so pentode as triode.

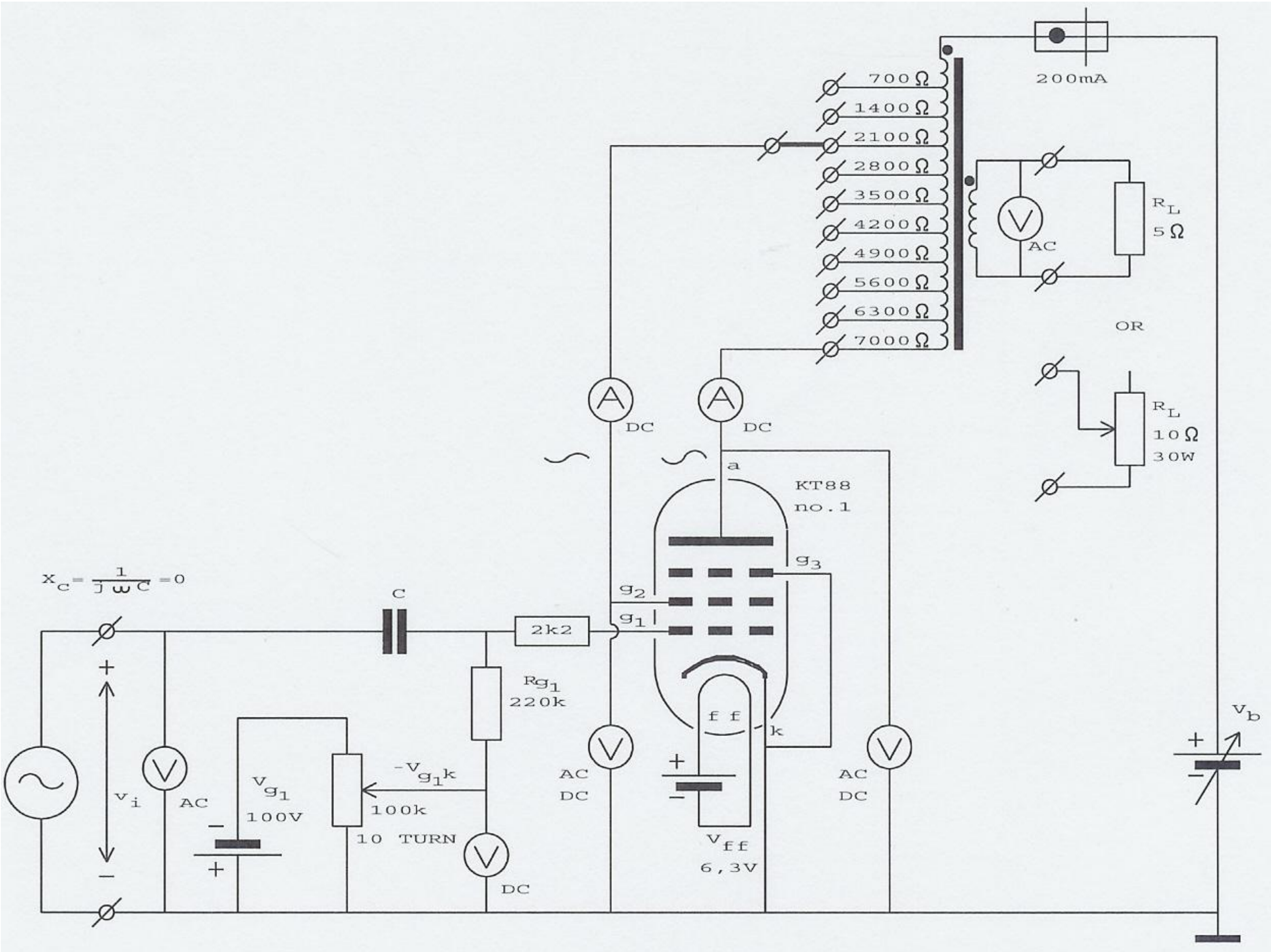
Table 3. Measured values of **line 3**						
V_{ak} (V) adjusted	I_a (mA) read on I_a-axis	I_{g2} (mA) measured	$V_{g2,k}$ (V) adjusted to achieve the read I_a	ΔV_{ak} (V) [300V – V_{ak}]	$\Delta V_{g2,k}$ (V) [300V – $V_{g2,k}$]	$x = \dfrac{\Delta V_{g2,k}}{\Delta V_{ak}}$
0	0	0	unknown	300	unknown	unknown
25	6.5	3.8	206	275	94	0.34
50	13	12.5	237	250	63	0.25
75	19.5	16	251	225	49	0.22
100	26	13	254	200	46	0.23
125	32.5	10.4	259	175	41	0.23
150	39	8	263	150	37	0.25
175	45.5	7	269	125	31	0.25
200	52	6.5	275	100	25	0.25
225	58.5	6.5	281	75	19	0.25
250	65	6.5	288	50	12	0.24
275	71.5	6.5	294	25	6	0.24
300	78	7.1	300	0	0	unknown

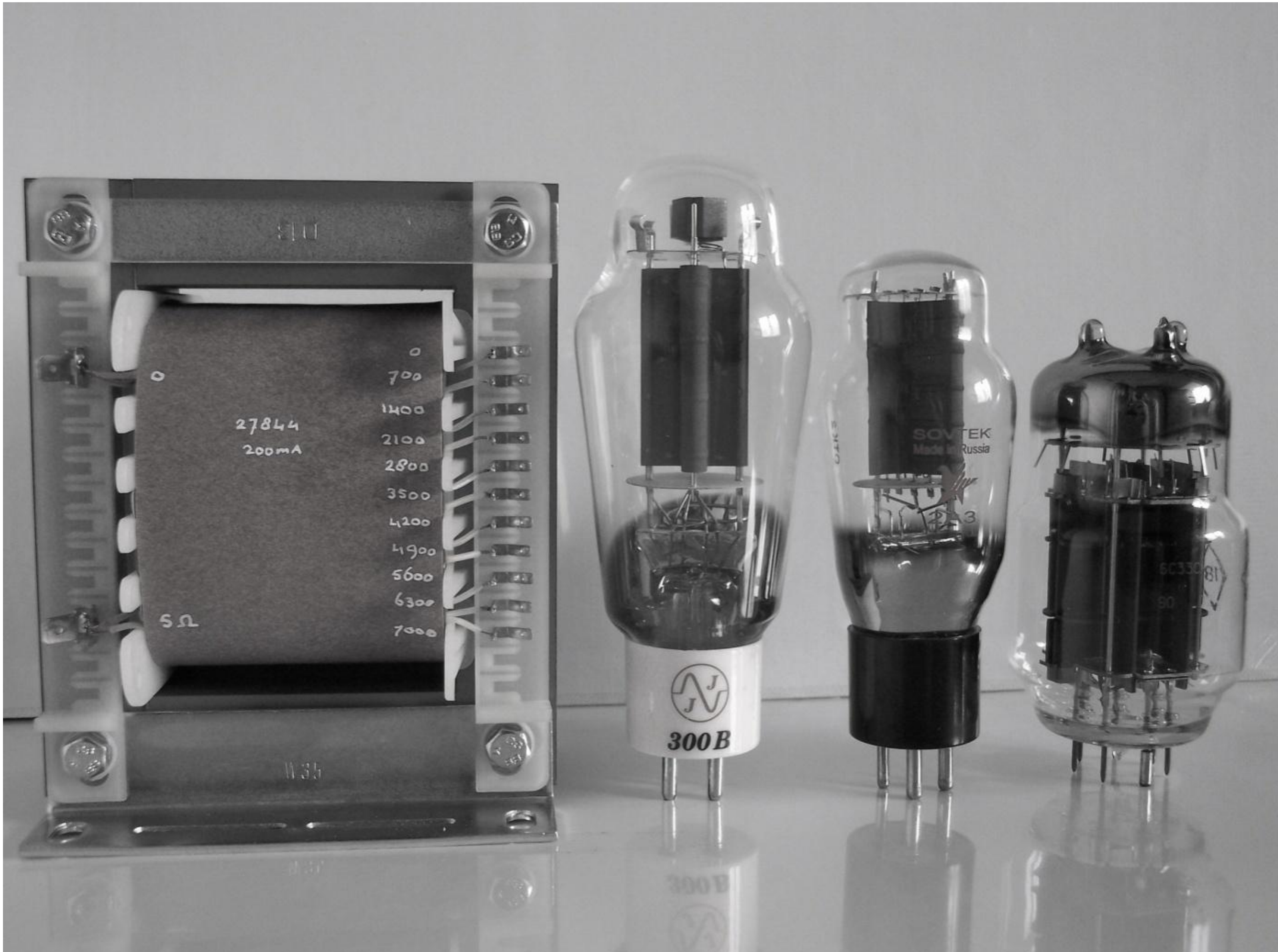
The average value of all screen grid primary transformer taps $x_{average}$ = 0.25. This value is mentioned at line 3. For this specimen KT88-1 we have pure ultra-linear at x = 0.25.

Table 5. Measured values of **line 5**						
V_{ak} (V) adjusted	I_a (mA) read on I_a-axis	I_{g2} (mA) measured	$V_{g2,k}$ (V) adjusted to achieve the read I_a	ΔV_{ak} (V) [300V – V_{ak}]	$\Delta V_{g2,k}$ (V) [300V – $V_{g2,k}$]	$x = \dfrac{\Delta V_{g2,k}}{\Delta V_{ak}}$
0	1	54	300	300	0	0.00
25	60	30	300	275	0	0.00
50	60	30	300	250	0	0.00
75	61	28	300	225	0	0.00
100	63	22	300	200	0	0.00
125	65	19	300	175	0	0.00
150	68	14	300	150	0	0.00
175	70	12	300	125	0	0.00
200	72	9.5	300	100	0	0.00
225	74	8.5	300	75	0	0.00
250	75	7.8	300	50	0	0.00
275	76	7.2	300	25	0	0.00
300	77	7.0	300	0	0	unknown
325	78	6.5	300	Not further than point W	Not further than point W	Not further than point W
350	79	6.3	300			
375	80	6.0	300			
400	80	6.0	300			

The adjustment of $V_{g2,k}$ happens automatically of course, because the screen grid is connected to V_b.
The screen grid primary transformer tap $x = 0.00$ but that will surprise nobody, so pentode as pentode.

6. Test equipment




0
27844
200mA
5Ω
0
700
1400
2100
2800
3500
4200
4900
5600
6300
7000
300B
SOVTEK
Made in Russia

Working point:

$V_{ak,w} = 300 \text{ V}$
$I_{a,w} = 80 \text{ mA}$
$V_{g1,kw} = -26 \text{ V}$
$V_{g2,kw} \approx 300 \text{ V}$

Input signal for each value of x:

$v_{g1,k} = 3.72\ V_{RMS}$

Given at $V_{ak} = 300\text{V}$ for KT88:

$S = 11.5 \text{ mA/V}$
$r_i = 12 \text{ k}\Omega$
$\mu = 138$
$S_2 = 1.15 \text{ mA/V}$
$\mu_{g2,g1} = 8$

$r_a = 7000\ \Omega$

$$A_a = \frac{v_{ak}}{v_{g1,k}} = -\frac{(S + x \cdot S_2) \cdot r_a}{1 + \left(\frac{x}{\mu_{g2,g1}} + \frac{1}{\mu}\right) \cdot (S + x \cdot S_2) \cdot r_a}$$

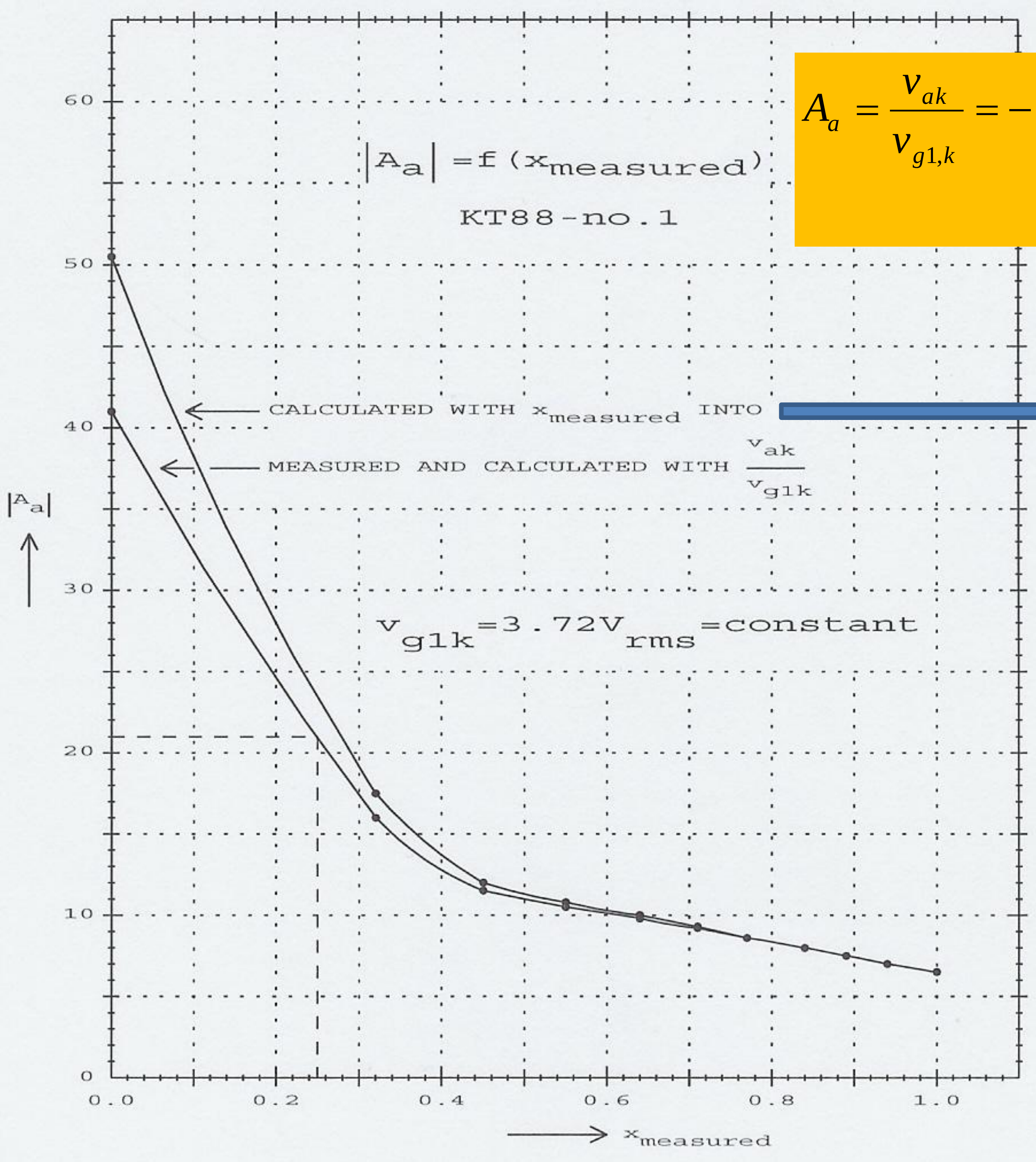
$$r_{out} = \left(\frac{n_s}{n_p}\right)^2 \cdot \frac{1}{(S + x \cdot S_2) \cdot \left(\frac{x}{\mu_{g2,g1}} + \frac{1}{\mu}\right)}$$

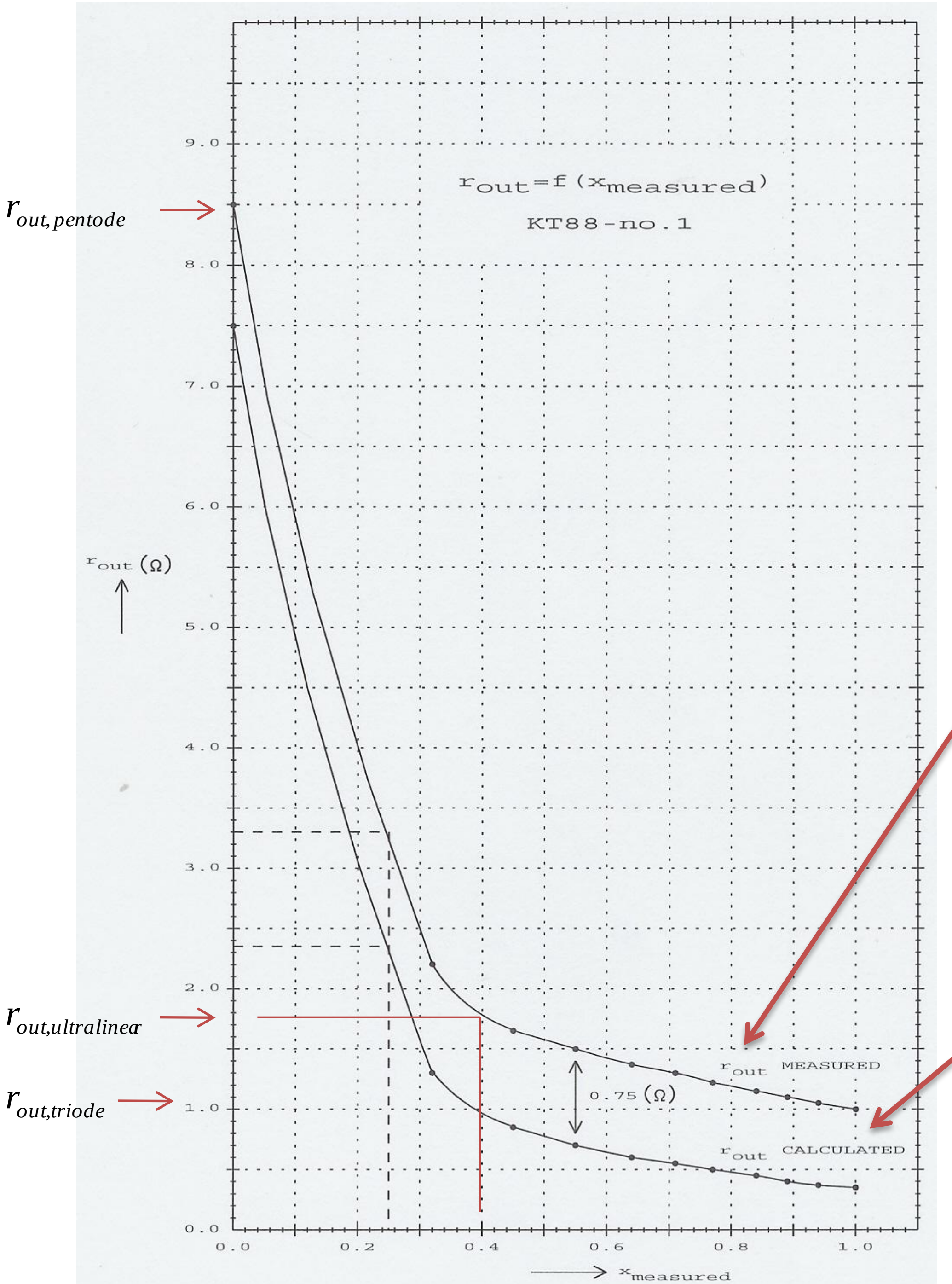
7. Practical evidence 1 of the network analyses of the Ultra Linear Amplifier

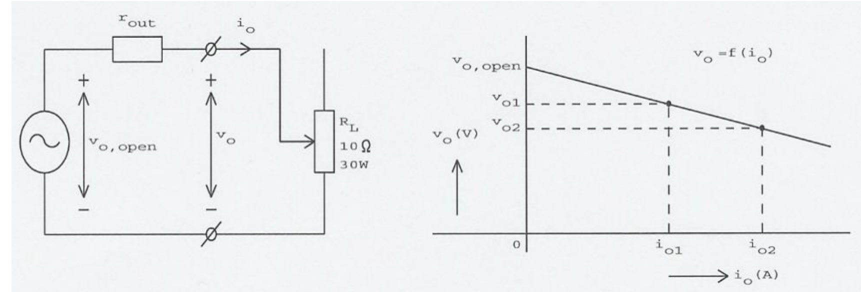
Table 6

x	$v_{g1,k}$ (V_{RMS})	v_{ak} (V_{RMS})	$v_{g2,k}$ (V_{RMS})	$x_{measured} = \frac{v_{g2,k}}{v_{ak}}$	p_a (W)	v_{RL} (V_{RMS})	p_{RL} (W)	$\lvert A_a \rvert = \frac{v_{ak}}{v_{g1,k}}$ measured	$\lvert A_a \rvert$ calculated by formula
0.00	3.72	158.0	0	0.00	3.60	4.01	3.20	42.4	50.6
0.10	3.72	60.8	19.2	0.32	0.53	1.51	0.45	16.3	16.8
0.20	3.72	47.7	21.3	0.45	0.33	1.22	0.29	12.8	13.3
0.30	3.72	40.7	22.3	0.55	0.24	1.01	0.20	10.9	11.3
0.40	3.72	36.1	23.2	0.64	0.19	0.92	0.16	9.7	10.1
0.50	3.72	33.4	23.6	0.71	0.16	0.83	0.14	9.0	9.3
0.60	3.72	30.9	23.9	0.77	0.14	0.78	0.12	8.3	8.7
0.70	3.72	28.9	23.2	0.84	0.12	0.73	0.11	7.8	8.1
0.80	3.72	27.3	24.2	0.89	0.11	0.69	0.10	7.3	7.7
0.90	3.72	26.1	24.6	0.94	0.10	0.65	0.09	7.0	7.3
1.00	3.72	25.0	25.0	1.00	0.09	0.62	0.08	6.6	7.0

$$A_a = \frac{v_{ak}}{v_{g1,k}} = -\frac{(S + x\cdot S_2)\cdot r_a}{1 + \left(\frac{x}{\mu_{g2,g1}} + \frac{1}{\mu}\right)\cdot (S + x\cdot S_2)\cdot r_a}$$







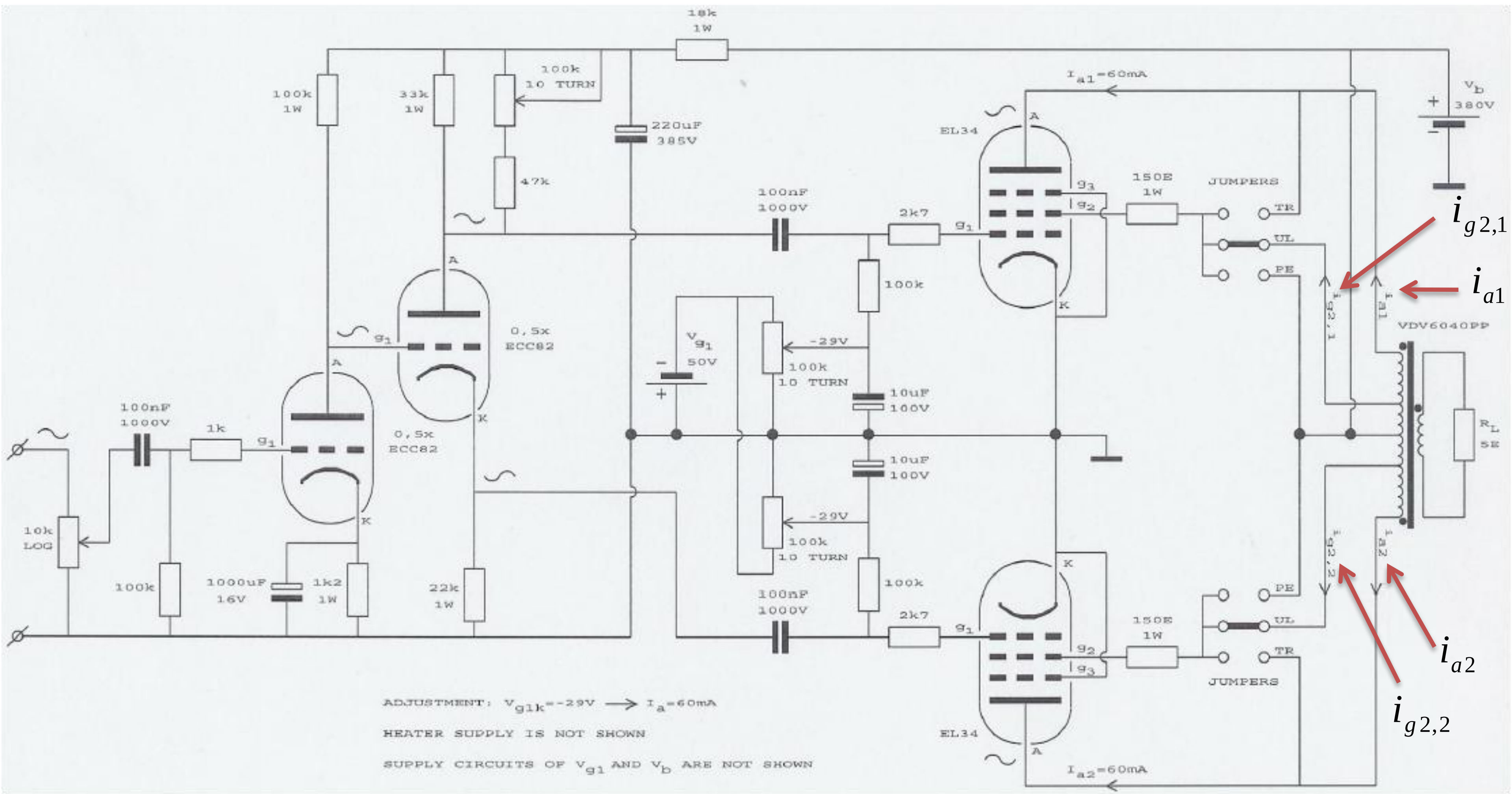
$$r_{out} = \frac{(v_{o1} - v_{o2})}{|i_{o1} - i_{o2}|}$$

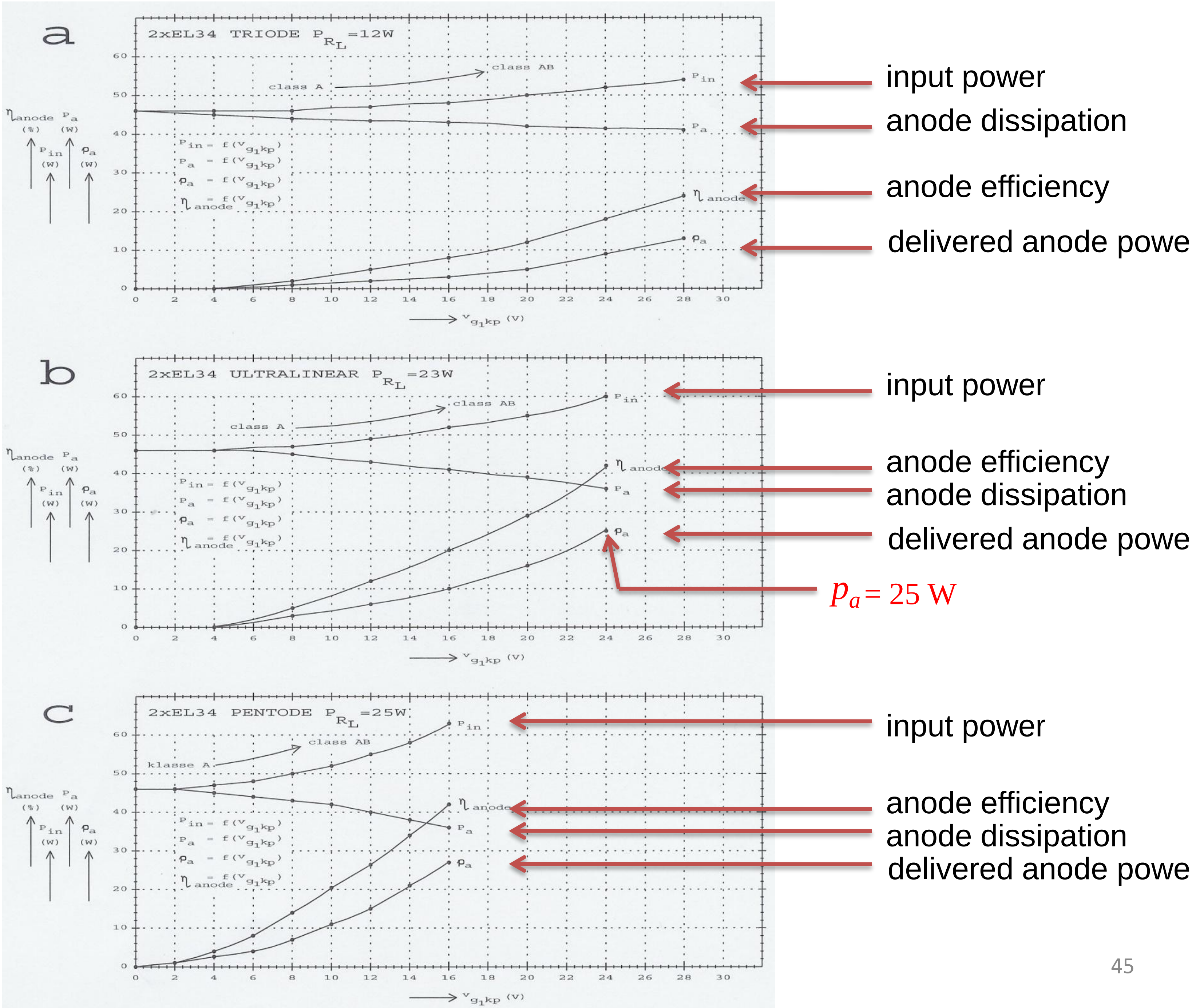
$$r_{out} = \left(\frac{n_s}{n_p}\right)^2 \cdot \frac{1}{(S + x \cdot S_2) \cdot \left(\frac{x}{\mu_{g2,g1}} + \frac{1}{\mu}\right)}$$

8. Comparison of practical powers and efficiencies of an amplifier in Triode mode, in Ultra Linear mode and in Pentode mode

My first electron tube amplifier according to a design from Menno's first book.

Schematic diagram of my first electron tube amplifier

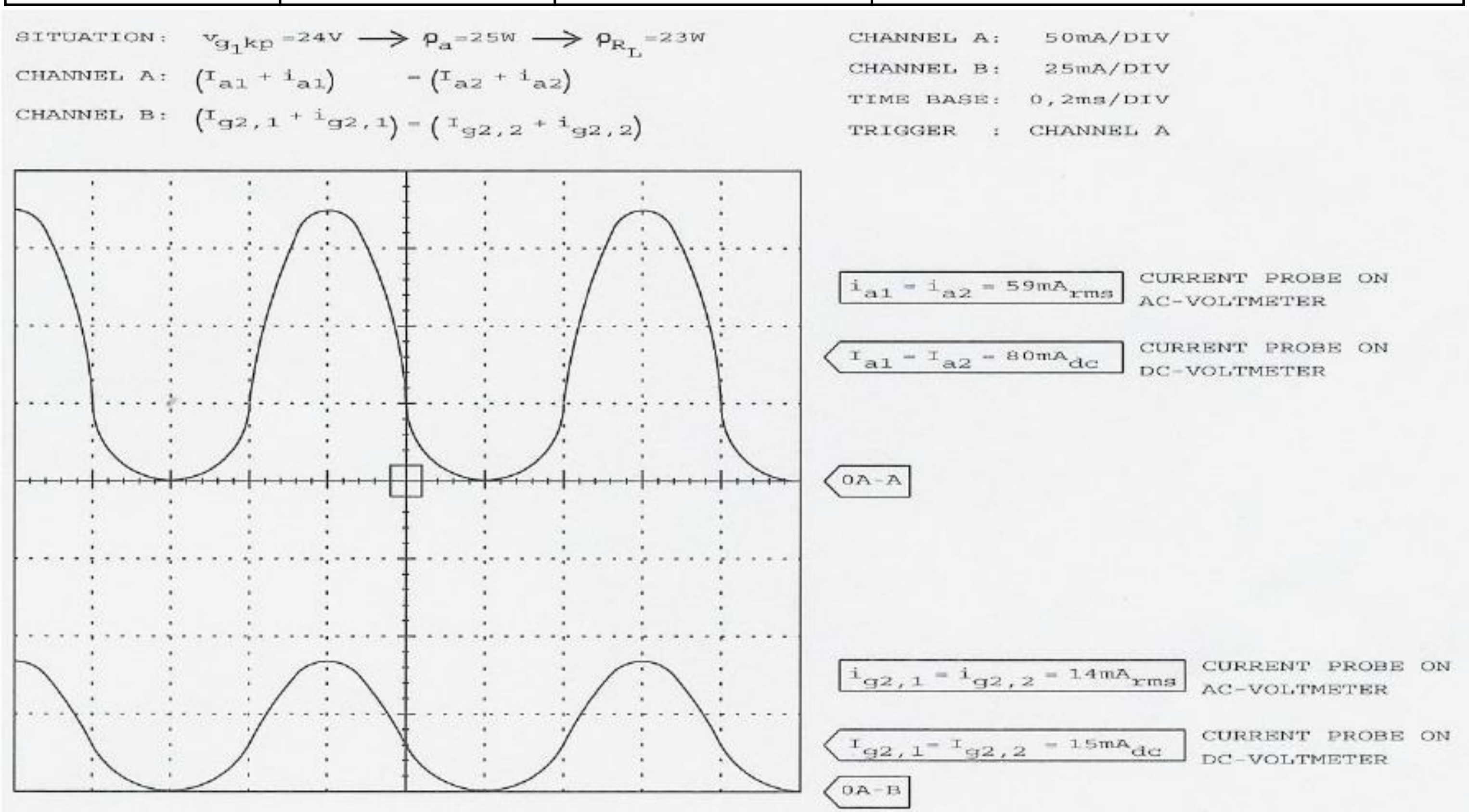




a
2xEL34 TRIODE PRL =12W
class A
class AB
Pin
Pa
ηanode
input power
anode dissipation
anode efficiency
delivered anode power
b
2xEL34 ULTRALINEAR PRL =23W
class A
class AB
input power
anode efficiency
anode dissipation
delivered anode power
p_a = 25 W
c
2xEL34 PENTODE PRL =25W
klasse A
class AB
input power
anode efficiency
anode dissipation
delivered anode power
Pin = f(vg1kp)
Pa = f(vg1kp)
ηanode = f(vg1kp)
vg1kp (V)
ηanode (%)
Pa (W)
Pin (W)

9. Practical evidence 2 of the network analyses of the Ultra Linear Amplifier

Table 7.			
v_{ak} (V_{RMS})	$v_{g2,k}$ (V_{RMS})	$x_{measured} = \dfrac{v_{g2,k}}{v_{ak}}$	given x of power transformer VDV6040PP
31.1	12.5	0.402	0.400
100.0	40.1	0.401	0.400
193.6	78.0	0.403	0.400



$$i_{a1} = i_{a2} = i_{a,measured} = 59\ mA_{RMS} \quad \text{and} \quad i_{g2,1} = i_{g2,2} = i_{g2,measured} = 14\ mA_{RMS}$$

Substitution of these currents in:

$$i_{total} = i_{a,measured} + x \cdot i_{g2,measured}$$

$$i_{total} = 59 + 0.4 \times 14 = 59 + 5.6$$

$$i_{total} = 64.5\ mA$$

Anode AC external resistance: $r_a = \frac{1}{2} \cdot r_{aa,VDV6040PP} = \frac{1}{2} \times 6000\ \Omega = 3000\ \Omega$

We have seen that the total anode power is 25W ⟹ $p_{a,EL34} = 12.5\ W$

$$p_{a,EL34} = \frac{v_{ak}^2}{r_a} \Rightarrow 12.5 = \frac{v_{ak}^2}{3000} \Leftrightarrow v_{ak} = \sqrt{12.5 \times 3000} = 193.6\ V_{RMS}$$

For determination of i_{total} apply: $i_{total} = i_{a,measured} + x \cdot i_{g2,measured} = \frac{v_{ak}}{r_a}$

$$i_{total} = \frac{v_{ak}}{r_a} = \frac{193.6}{3000} = 0.0645\ A$$

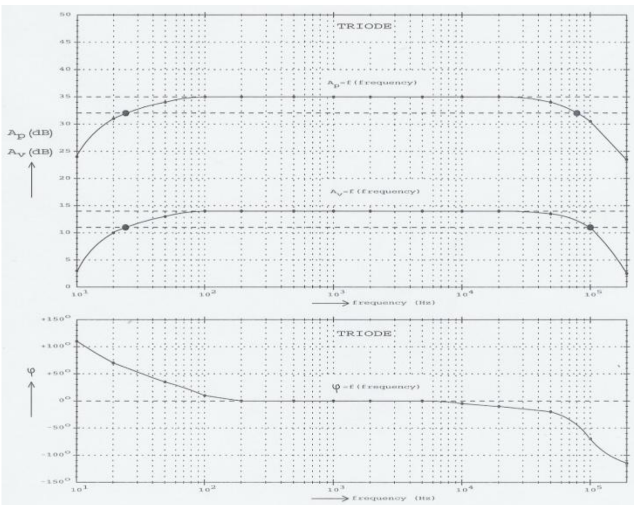
$$i_{total} = 64.5\ mA$$

The effect of this fictive i_{total} is an anode power of 12.5 W for one power pentode.

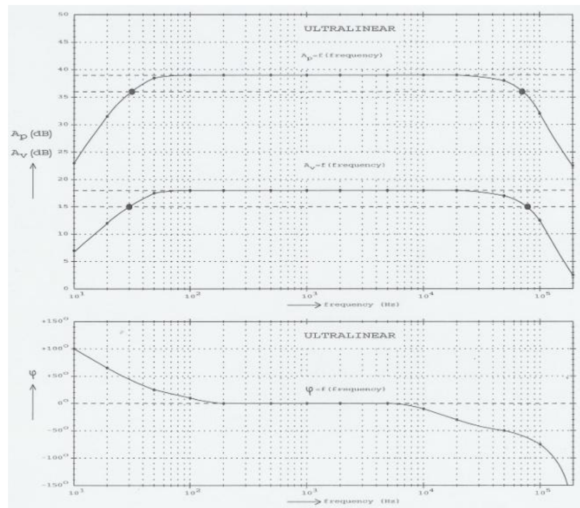
The effect of $(i_{a,measured} + x \cdot i_{g2,measured})$ is an anode power of 12.5 W for one power pentode.

10. Comparison of practical frequency behavior of an amplifier in Triode, Ultra Linear and Pentode mode.

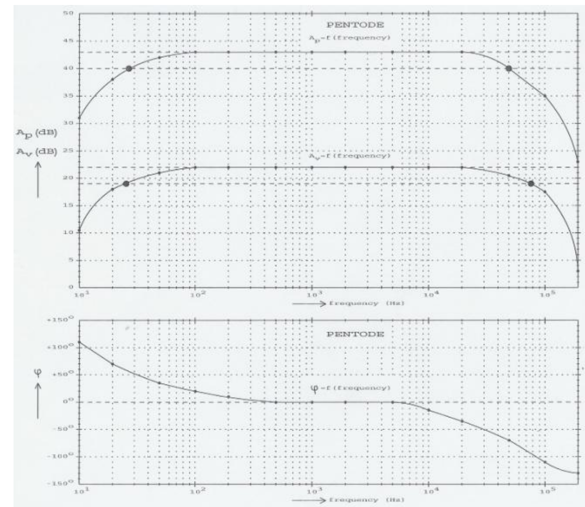
Triode



Ultra-Linear



Pentode



15 Hz

80 kHz

21 Hz

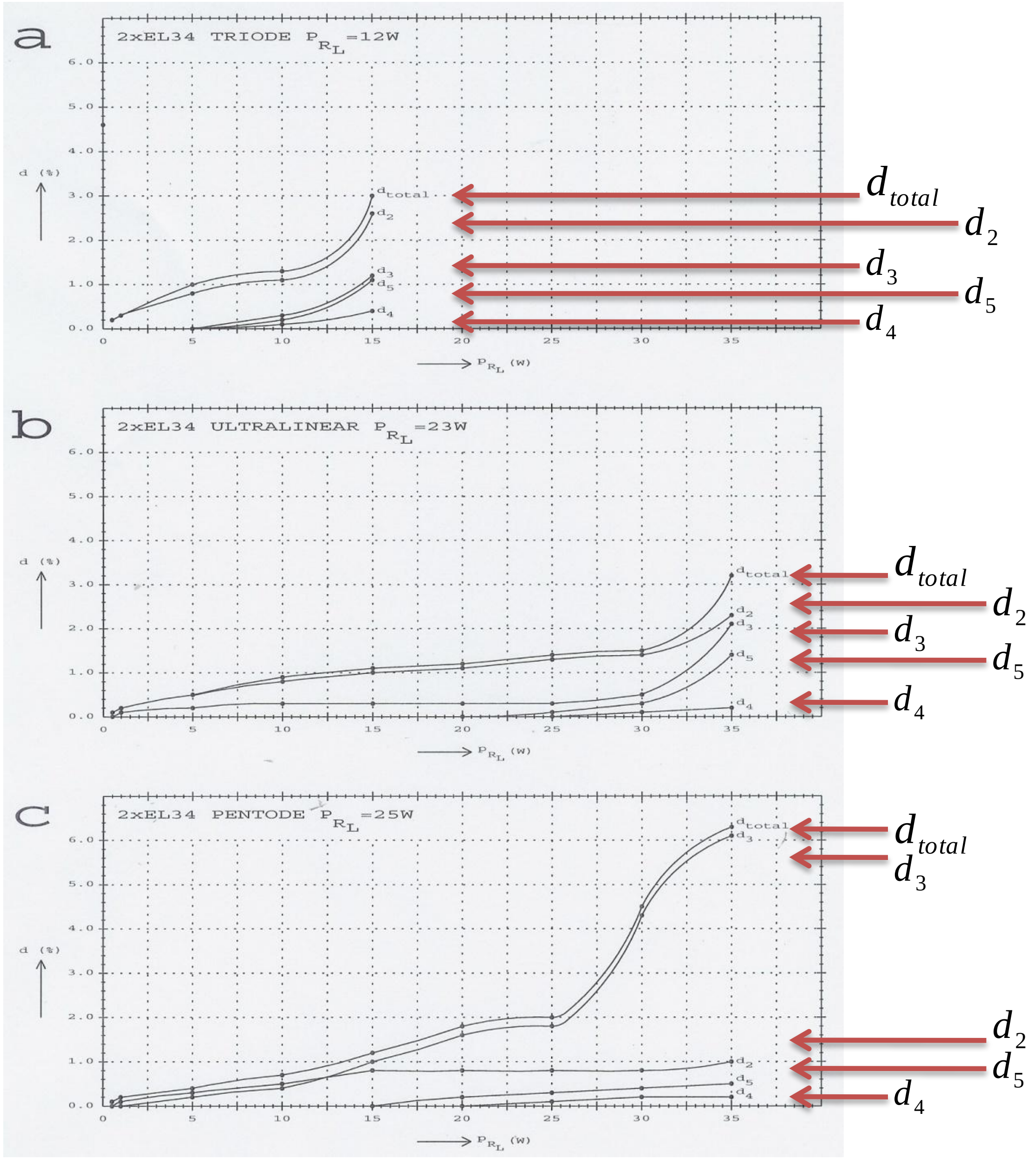
70 kHz

18 Hz

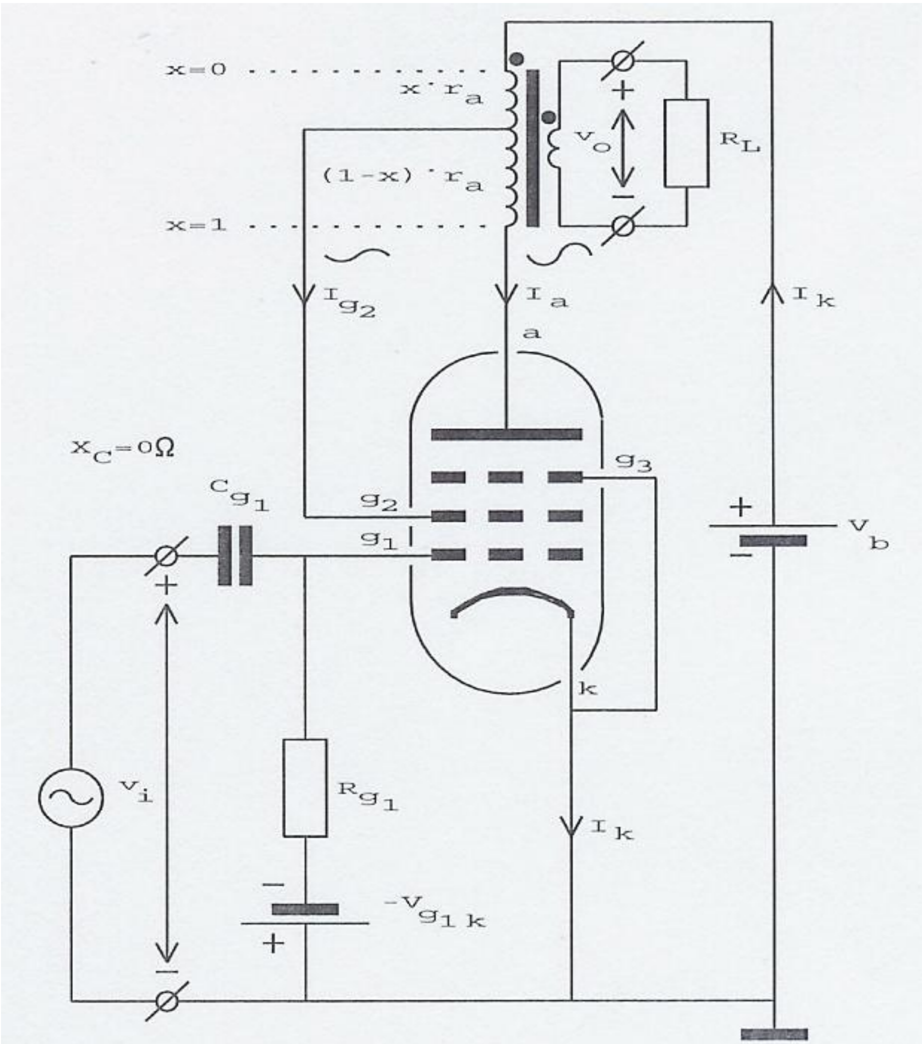
50 kHz

Differences in frequency and phase characteristics are small.
The parasitic capacitances due to the Miller effect are <u>not</u> negligible for triodes, but their anode AC internal resistance is low.
The parasitic capacitances due to the Miller effect are negligible for pentodes, but their anode AC internal resistance is high.
The limiting of 3dB-high is mainly due to the limiting bandwidth of the transformer.

11. Comparison practical non-linear distortion of an amplifier in Triode mode, Ultra Linear mode and Pentode mode



Final summary



These formulae match in theory and practice.

$$A = \frac{v_o}{v_i} = -\frac{n_s}{n_p} \cdot \frac{(S + x \cdot S_2) \cdot r_a}{1 + \left(\frac{x}{\mu_{g2,g1}} + \frac{1}{\mu} \right) \cdot (S + x \cdot S_2) \cdot r_a}$$

$$r_{out} = \left(\frac{n_s}{n_p} \right)^2 \cdot \frac{1}{(S + x \cdot S_2) \cdot \left(\frac{x}{\mu_{g2,g1}} + \frac{1}{\mu} \right)}$$

x is the variable and the other quantities are almost constant (in theory).

The contribution of the anode AC to the delivered output power is much more than the contribution of the screen grid AC because in practice: $x \approx 0.4$ and $i_{g2} = 0.2 \cdot i_a$

$$\frac{v_{ak}}{r_a} = -\left(i_a + x \cdot i_{g2}\right) = -i_{total}$$

It is possible to determine screen grid tap *x* for an ultra-linear application for each sample of a pentode after measuring the anode characteristics for both the triode and pentode configurations of that pentode.

The delivered output power at ultra-linear is slightly less than with pentode configuration.
The delivered output power at ultra-linear is much more than with triode configuration.

The configurations triode, ultra-linear and pentode have an almost equal audio bandwidth.

The ultra-linear configuration gives almost the same low non-linear distortion as the triode configuration.

The ultra-linear configuration has the "high power advantage" of the pentode configuration and the "low non-linear distortion advantage" of the triode configuration.

12. Bibliography