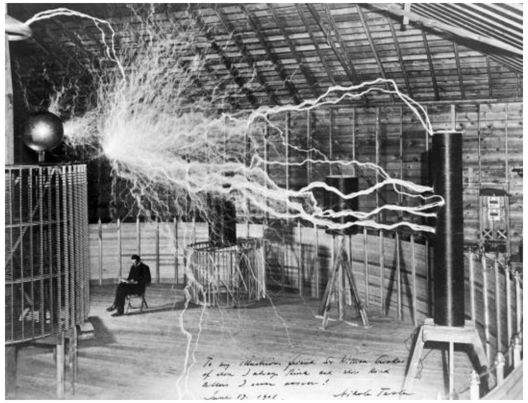
The ZOTL: An Alternative to the Output Transformer for Hi Fi Tube Amplifiers

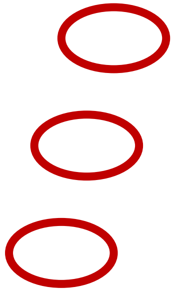
David Berning



Audio amplifier dilemma

Speakers like high current, low voltage.

Vacuum tubes like high voltage, low current.



Can they talk to each other?

Outline

I. The Output transformer - Why use one?
II. The OTL (Output Transformer Less)
III. The ZOTL

I. The Output Transformer- Why use one?

1) Power transfer efficiency; example tube current to speaker current, impedance conversion
2) Size matters
3) Single-Ended vs Push-Pull
4) Simplified parasitics model, frequency response
5) Special configuration: Ultra-Linear

Power transfer efficiency

Consider a common output tube, the 6V6 with a recommended average operating current of 40 mA. We wish to drive an 8-Ω speaker with this tube. If we connect the tube directly to the speaker we can, ideally, have a peak signal current in the voice coil of plus and minus 0.04 A. The peak power delivered to the speaker is:

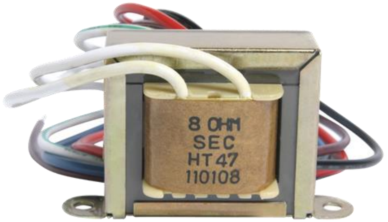
$$P = I^2 R \quad \textit{or alternatively} \quad P = V^2 / R$$

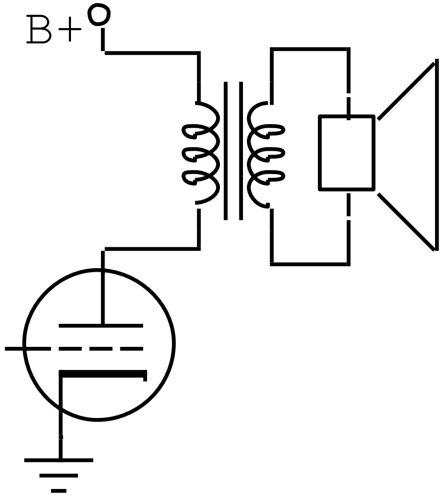
For this case, the limiting term is current so the first equation applies. Thus the peak power delivered to the 8-Ω speaker is 0.012 W; The RMS value is 0.006 W. Meanwhile the tube plate loss at a typical 6V6 operating voltage of 300 V is the voltage-current product or 12 W. The efficiency is 0.006/12, or 0.05 %!

But if I use an output transformer I can balance the two equations to take advantage of the high voltage. The transformer has the property of reflected impedance, so the turns ratio can be selected to make the power term equal for the above equations. If we assume a peak voltage of plus and minus 300 V is available on the primary of the transformer and the plate resistance of the 6V6 is zero, a turns ratio of 30 would transfer the most power. The impedance transfer ratio is 900, and the tube would “see” a speaker load of 7200 Ω. The peak power out is now 12 W, or 6 W RMS. In reality, the tube plate impedance is not zero, and the full 300 V voltage transition is not possible, so perhaps only a third of this power might end up at the speaker. But at 2 watts the efficiency is 16 %, with an improvement factor of 320.

Silvaweld OTL Reference 200, 30 output tubes per channel.

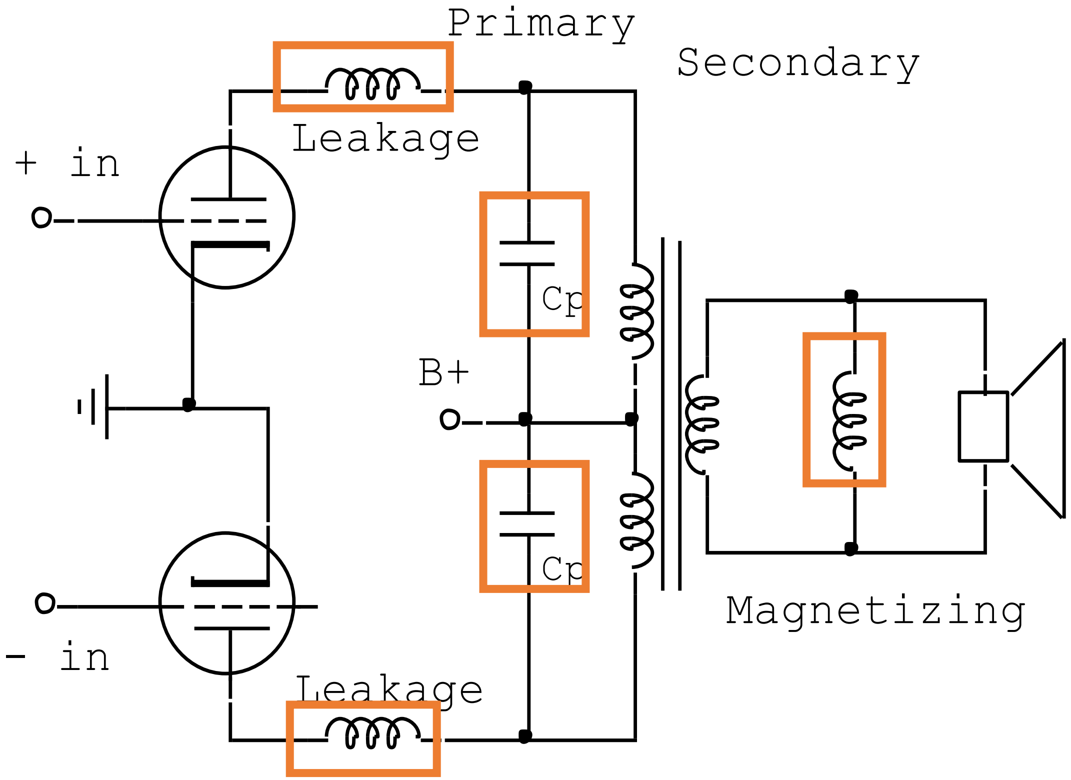
Small audio-output transformer-small sound.



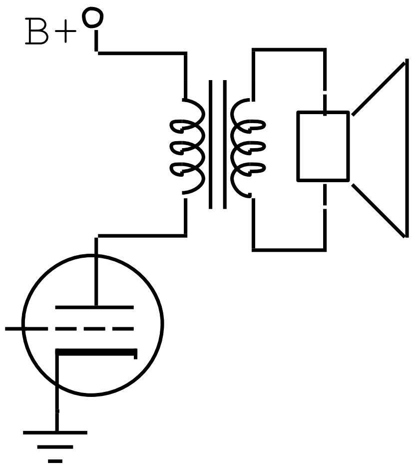


Big, heavy, and expensive audio-output transformer-big Hi-Fi sound.

Push-Pull vs Single-Ended



Push-Pull Output Transformer, including parasitic elements



Single-Ended Output Transformer, parasitic elements similar but not shown.

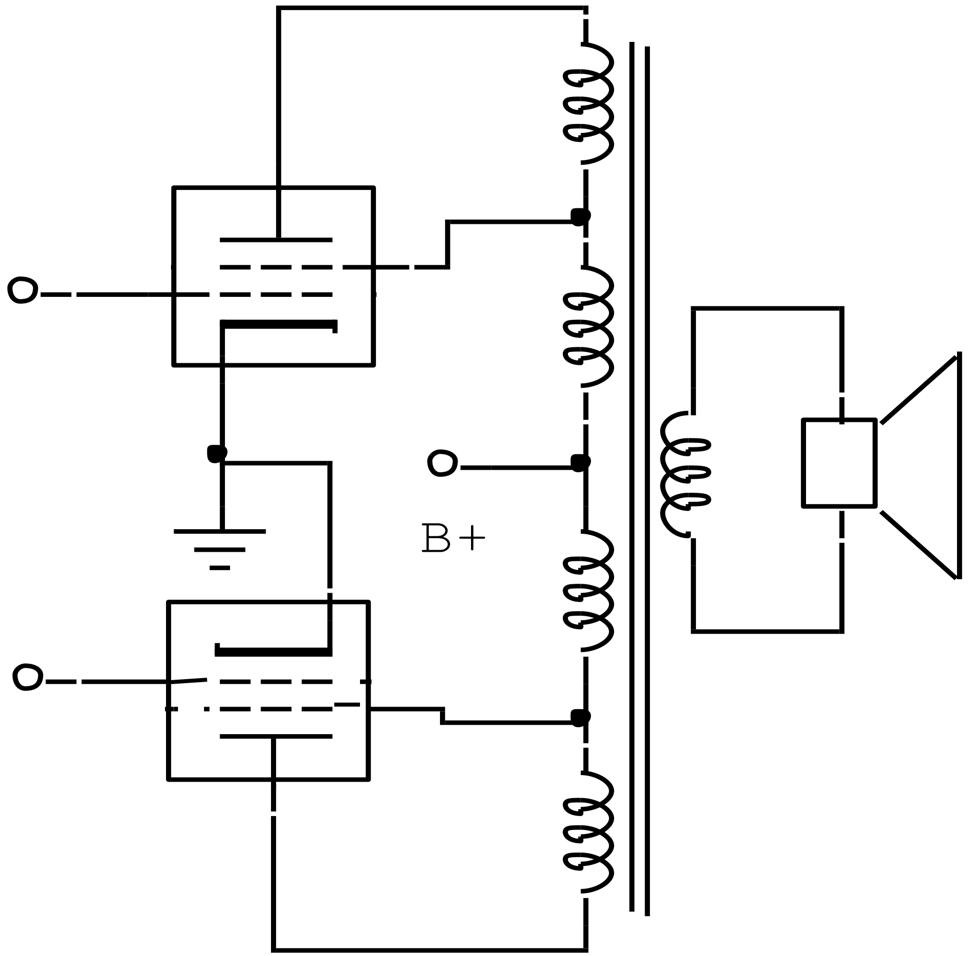
- P-P requires two tubes and two inputs, one inverted in phase; SE one input.

- Bandwidth limited at high frequencies by leakage inductance and parasitic capacitance in transformer or both.

- Low frequencies limited by magnetizing current and saturation or both.

- P-P can deliver much more power per tube than SE.

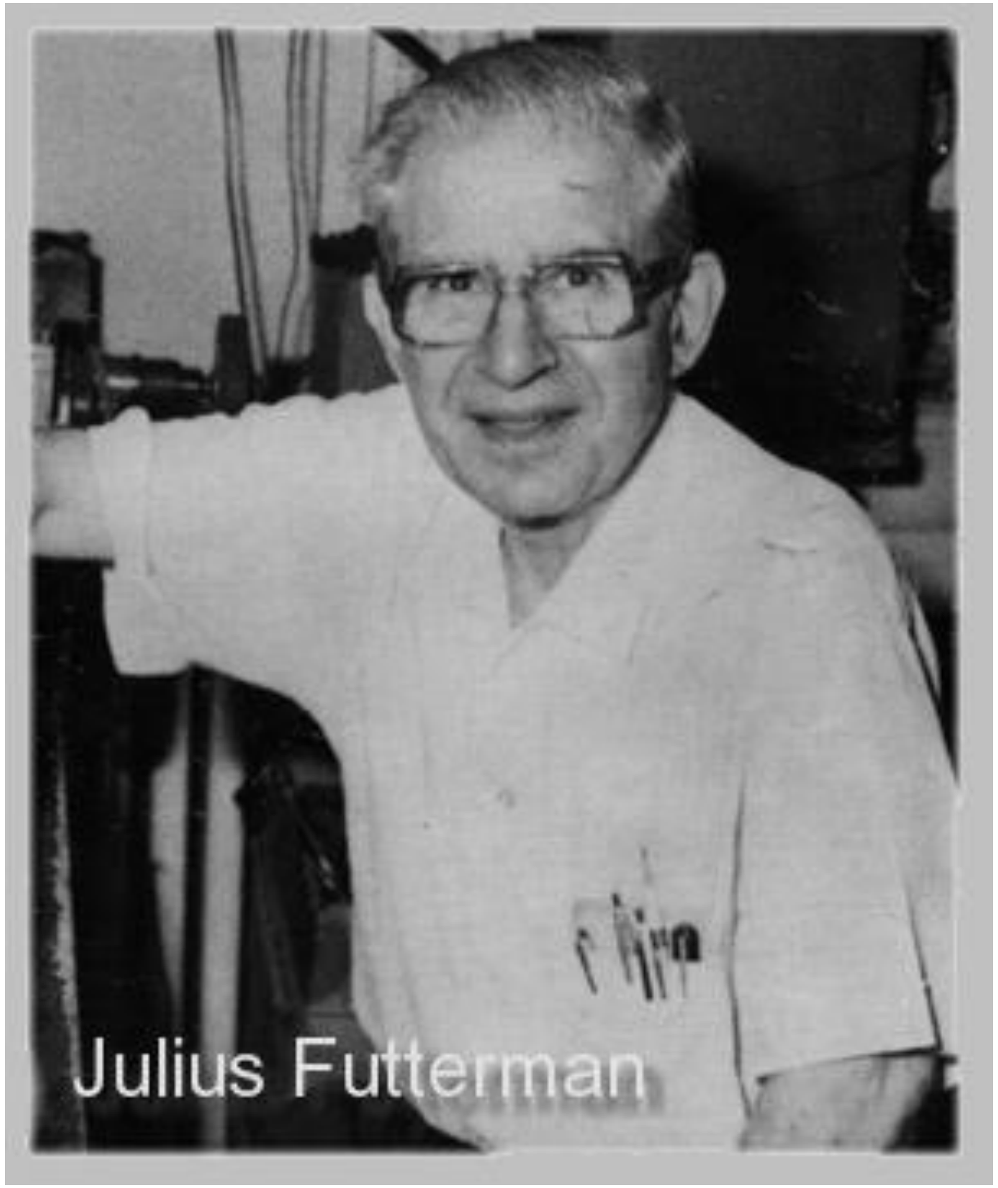
- SE requires air gap to store energy to provide bipolar current for speaker; parasitics made worse.



<u>Ultra-Linear</u> configuration adds some local feedback which lowers output impedance and distortion. The primary of the output transformer has taps on the windings to feed portions of the plate signal voltages to the screen inputs of the tubes. The dc component of voltage on the screens is nearly the same as that for the plates.

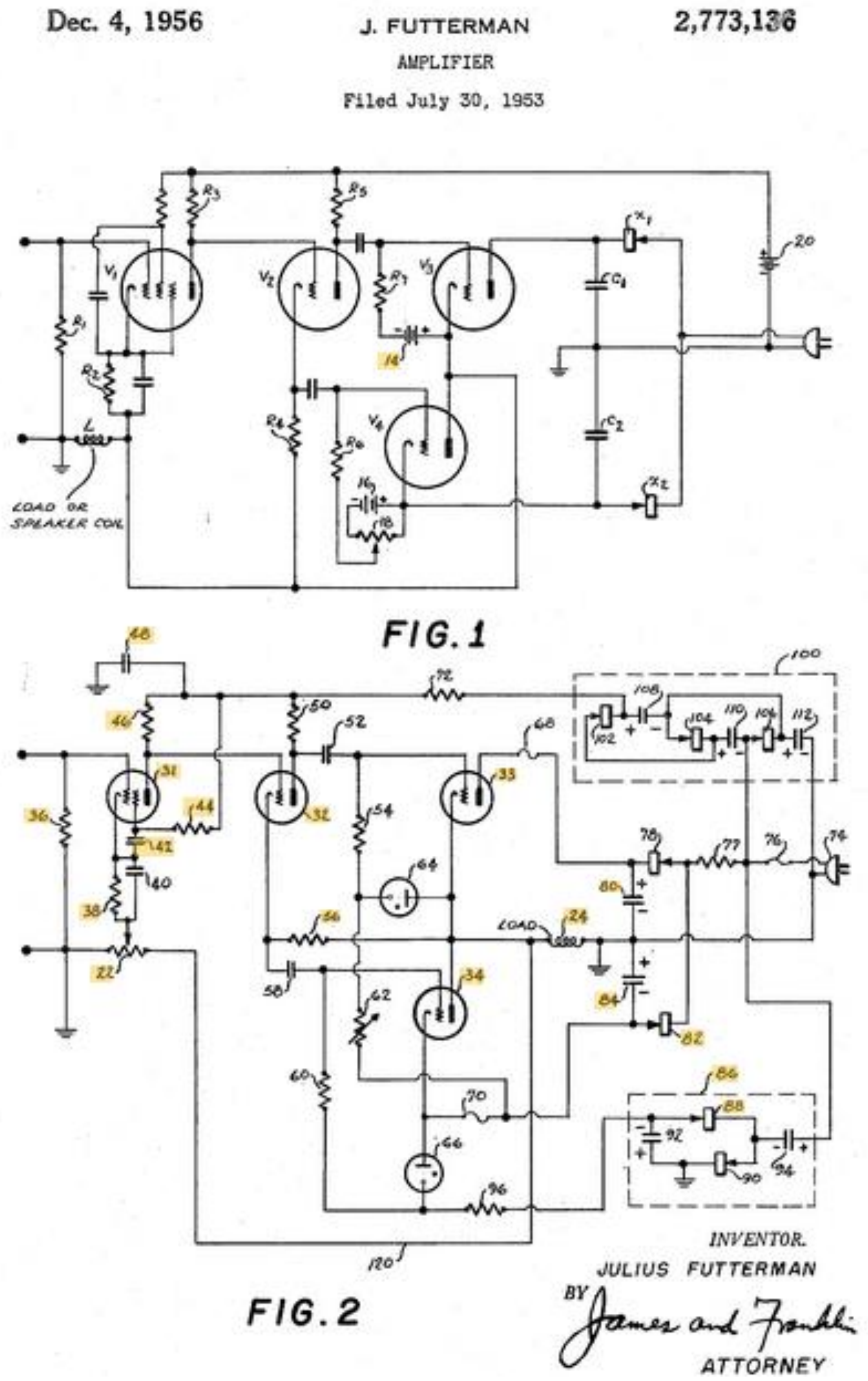
II. The OTL (Output Transformer Less)

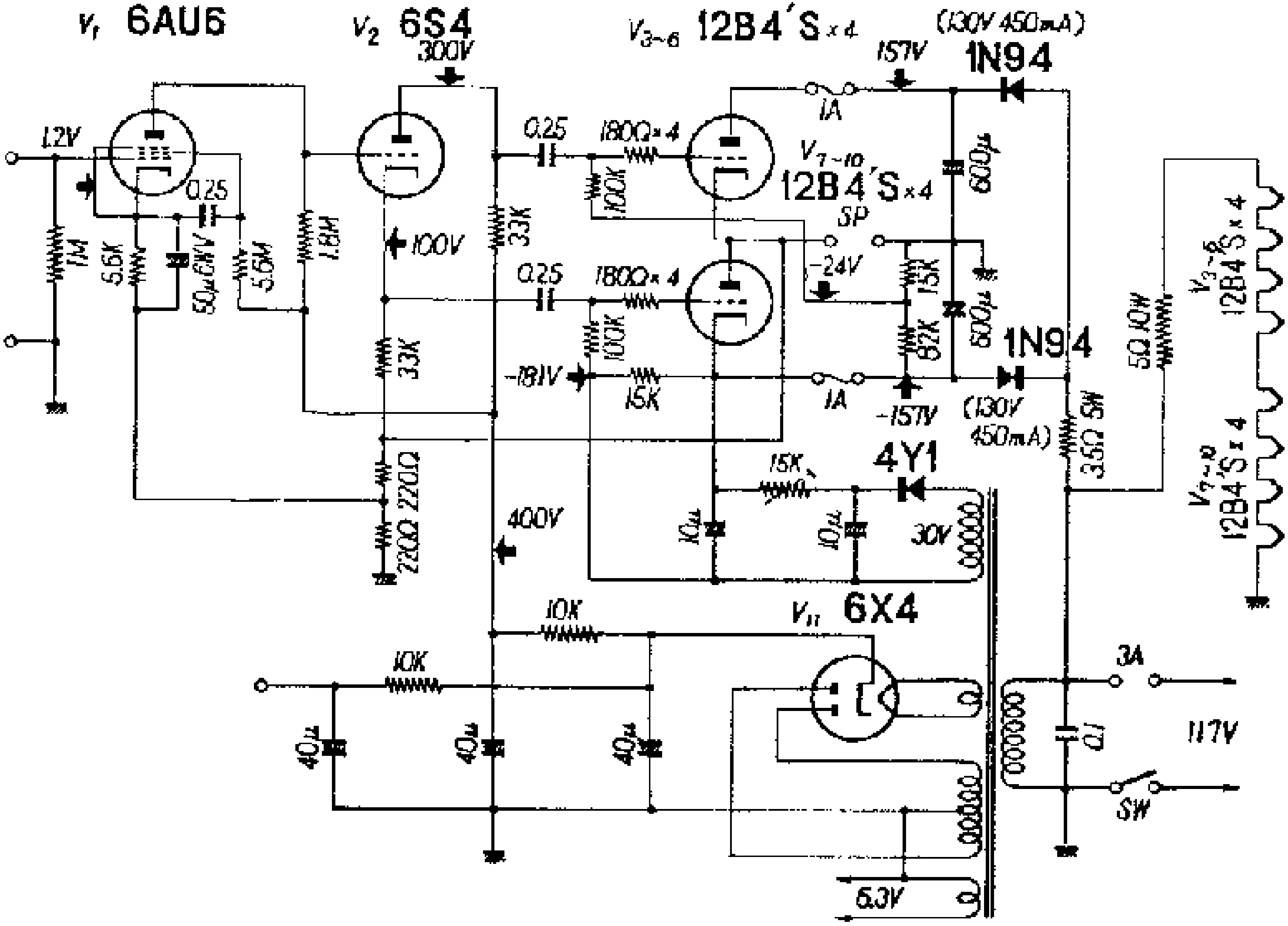
1) Futterman
2) Philips
3) Proliferation of OTLs



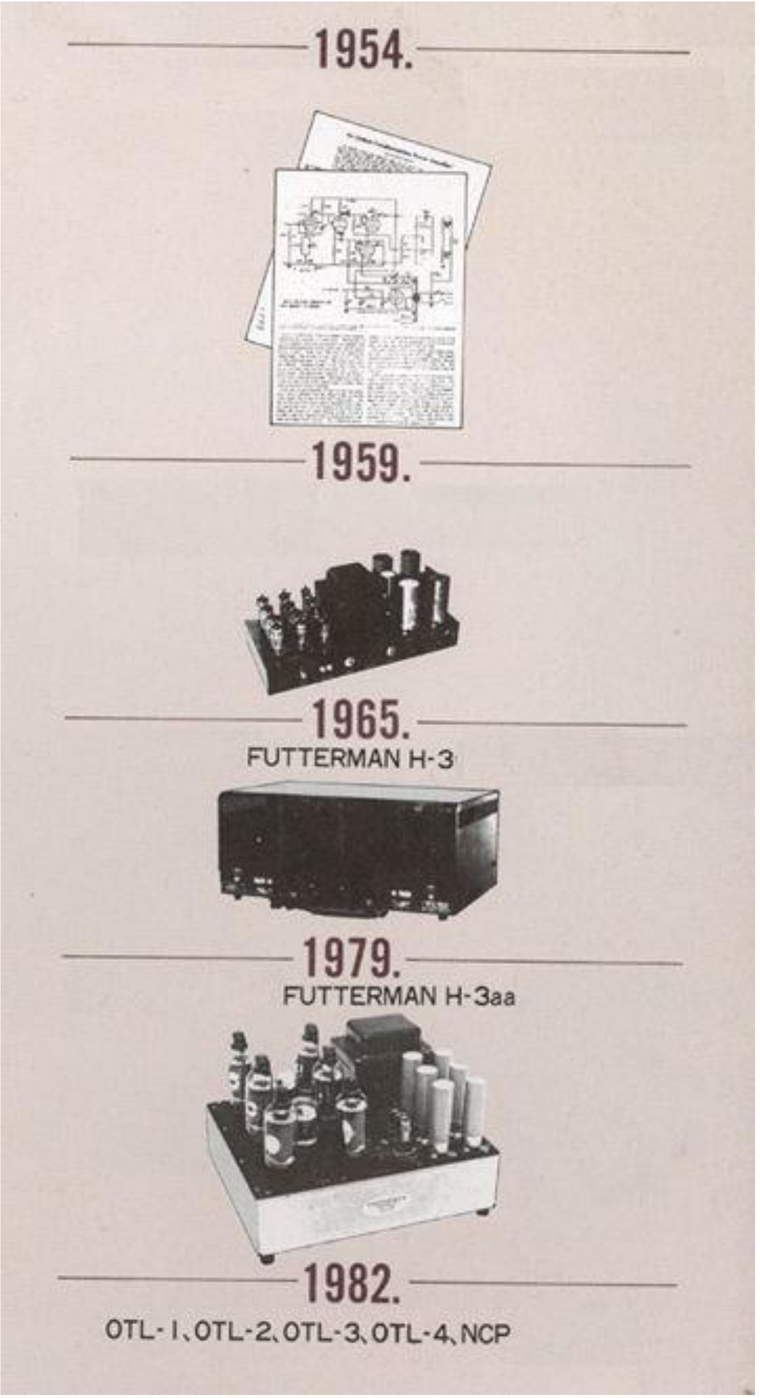
Julius Futterman is considered the father of the OTL amplifier. Born 13th October 1907 in New York, as a descendant of German immigrants. Died 12th September 1981 in New York. He had been working on designing tube-testing apparatus before his OTL development work and this gave him an advantage in understanding important tube attributes that would best suit his amplifier.

- 13 Claims. (Cl. 179-471) This invention relates to amplifiers, and more particularly to audio-frequency power amplifiers employing large amounts of negative feedback to reduce distortion, and is therefore useful in the reproduction of speech and music.





Original Futterman circuit. Note lack of safety isolation from line. This circuit appears to have at least 40 dB of negative feedback, an amount that would be impossible to achieve using an output transformer.

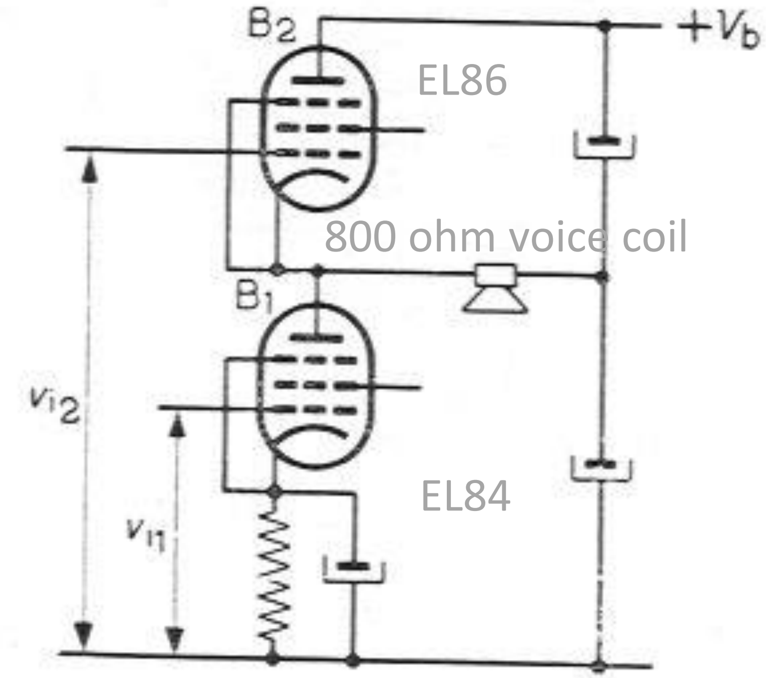


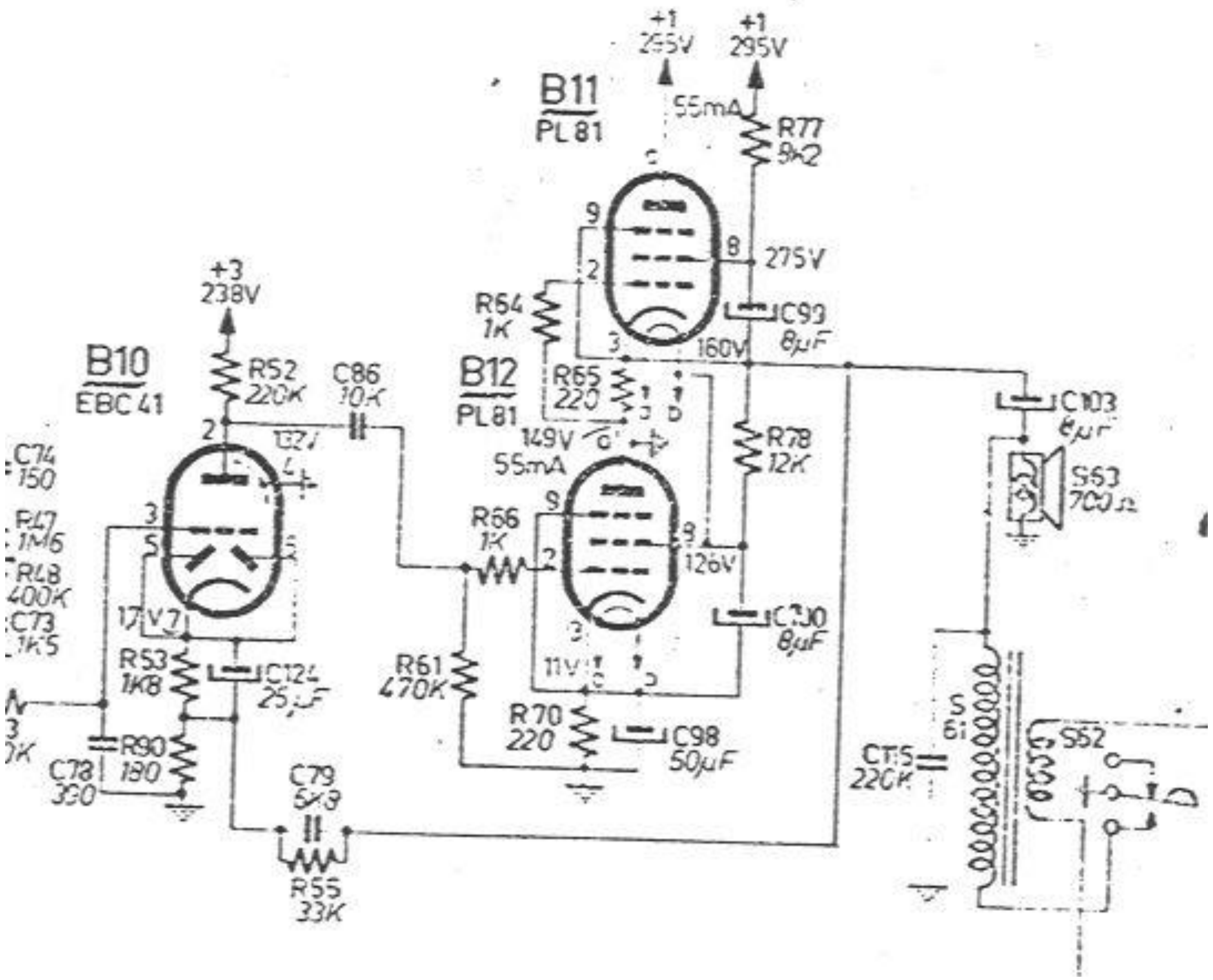
Time line of Futterman amplifiers. The designated 1959 offering is based on the patent with 4 pcs.12B4 triodes in parallel for the high side and 4 pcs. more for the low side. Mono, with about 10 watts output. The 12B4 is a vertical-deflection amplifier with plate resistance around 1000 ohms and an amplification factor of 6.5. The later Futterman offerings such as the H-3 and H-3aa used various (beam) horizontal sweep tubes ending with the 6LF6. When New York Audio Labs licensed the design from Futterman in or about 1981 they were able to continue without too many changes. But NYAL was fairly short lived; the Black Monday stock market crash of 1987 ended many high-end audio companies.

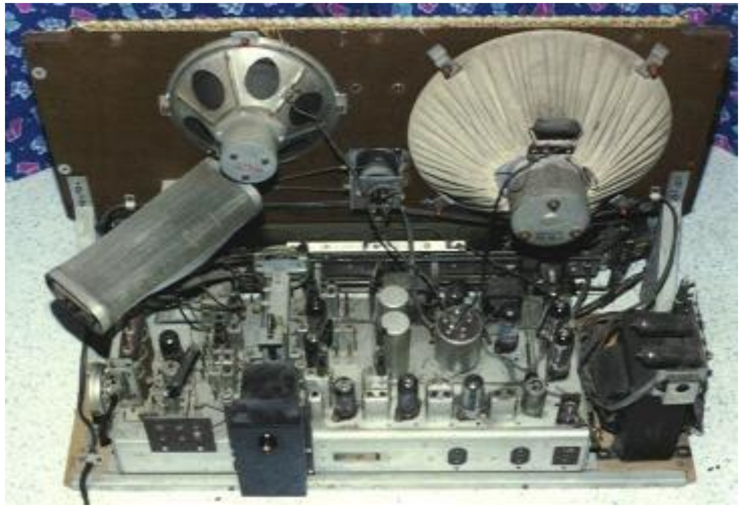
NYAL (New York Audio Labs) Harvey Rosenberg, Jon Syder, Ted Hammond, and George Kaye licensed the Futterman design and they made several versions (OTL-1, OTL-2, …etc.).

Principal of operation: Vi-1 main drive input bottom tube. Vi-2 inverted signal from Vi-1 of much higher amplitude to operate top tube as follower. It is likely that Vi-2 is derived from plate voltage of bottom tube rather than supplied separately for cost savings with some degradation in efficiency and power, unlike the Futterman that maintained separate drives.

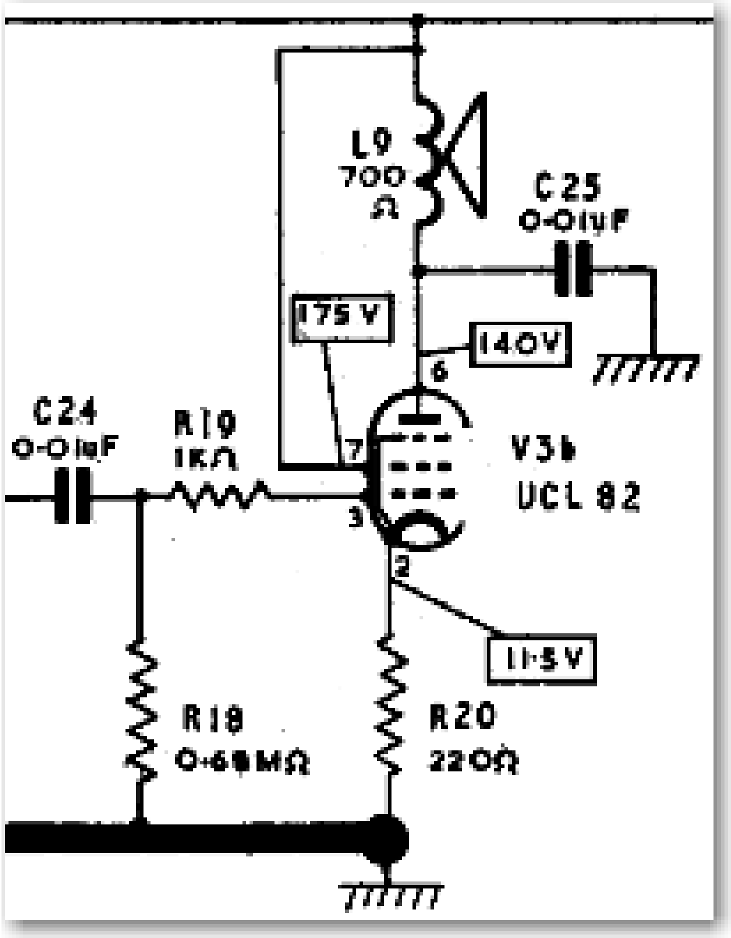
The Philips B4X61A has been reported to have superb sound. The EL86 and EL84 together form a push-pull output stage, but of the series type. The 800-ohm speaker is connected without an output transformer. (1956)







More deluxe Philips BX998A has OTL-driven 700-ohm speaker plus an output transformer for a conventional speaker. Note blocking capacitor for speaker and transformer. (1956)



Philips B2G25U

Stella ST113U

Cossor CR1202U

Superheterodyne 4-tube, AC-DC 220V-Early 1960s

Philips Hi Fi OTL amp for high-impedance speakers

CIRCA 1955 , MADE IN EINDHOVEN HOLLAND

Proliferation of OTL Amplifiers

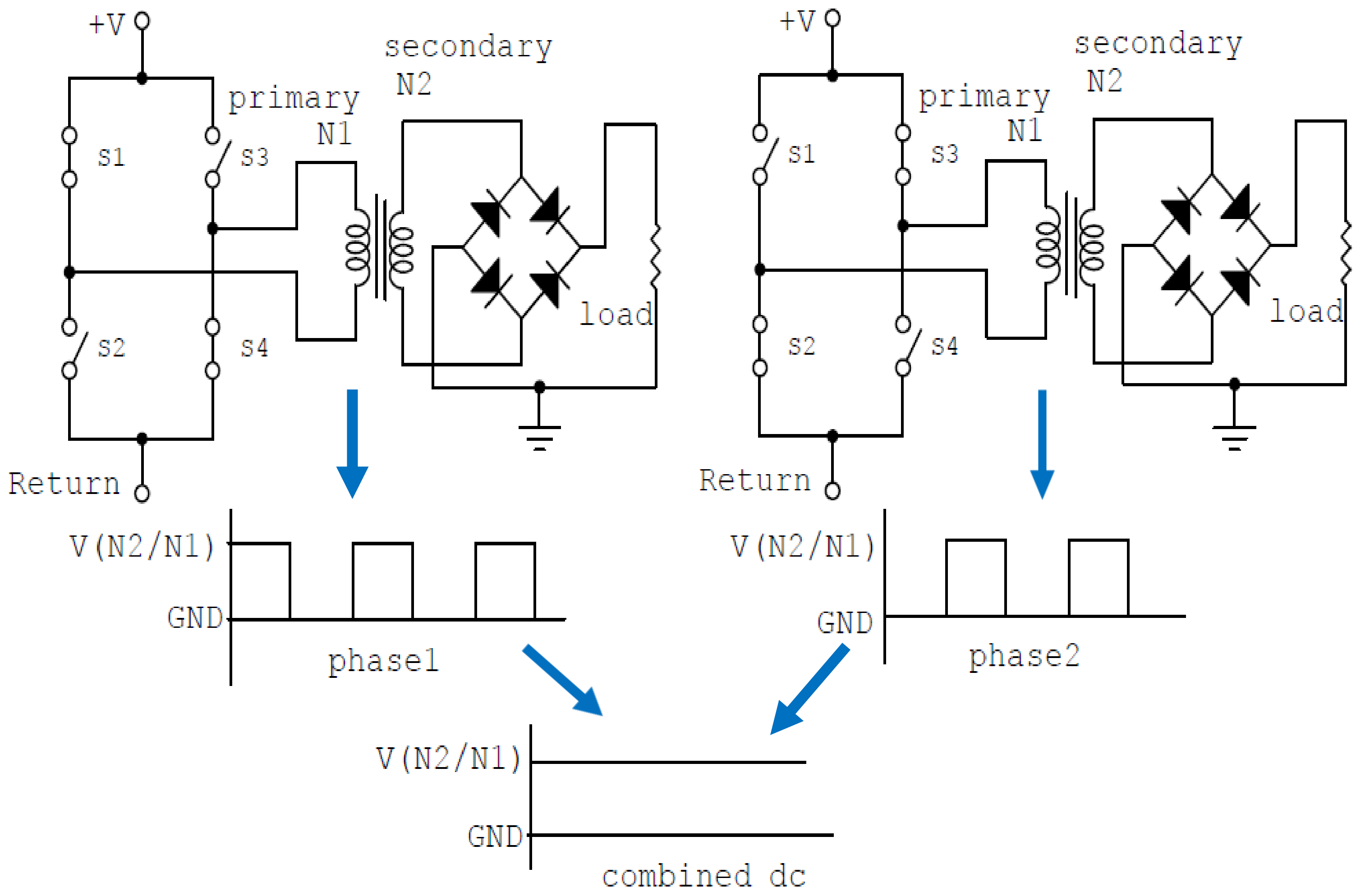
III. The ZOTL

1) DC-DC converters, really impedance conversion
2) Topology, patent
3) Single-Ended vs Push-Pull
4) Impedance conversion ratios-output transformer vs ZOTL, Reflected impedance
5) Frequency response limitations-Switching frequency
6) Special configuration: Ultra-Linear with ZOTL
7) Performance compared to output transformer

dc-dc power conversion

Fundamental to the ZOTL

S1 thru S4 form a full bridge made up of MOSFET power switches that alternately commutate the applied dc supply voltage to the primary of the transformer, first in one polarity and then in the opposite polarity. This applies ac to the transformer that can be stepped up or down in voltage.



The secondary ac voltage is converted back into dc voltage for the load by the full-wave bridge rectifier. In the ZOTL that load is a vacuum tube modulated in conductance by a varying audio signal.

A Quick Lesson

US005612646A

United States Patent [19]

Berning

[11] **Patent Number: 5,612,646**

[45] **Date of Patent: Mar. 18, 1997**

[54] **OUTPUT TRANSFORMERLESS AMPLIFIER IMPEDANCE MATCHING APPARATUS**

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[21] Appl. No.: **521,494**

[22] Filed: **Aug. 30, 1995**

[51] **Int. Cl.**[6] **H03F 3/38**

[52] **U.S. Cl.** **330/10**; 330/297

[58] **Field of Search** 330/10, 118, 123, 330/146, 297

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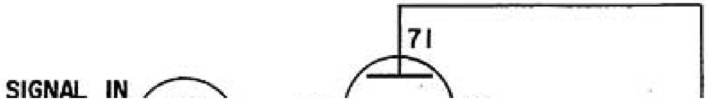
Primary Examiner—Steven Mottola
Attorney, Agent, or Firm—Fulbright & Jaworski L.L.P.

[57] **ABSTRACT**

A linear audio amplifier includes a push-pull pair of vacuum tubes operating in a linear amplification mode coupled through a pair of dc-dc switching power converters to an external load impedance. Each power converter includes a transformer with one or more secondary windings that drive rectifier circuits, and the resultant dc voltage sources are loaded by their respective tubes. The power input ports of two bridge power converters are connected in a series totem-pole fashion with the minus power input port of the top bridge connected to the plus power input port of the bottom bridge. A center-tapped fixed voltage source is connected across the two-bridge pair such that the positive voltage is connected to the plus power input port of the top bridge, and the negative voltage is connected to the minus power input port of the bottom bridge. One side of an external load impedance is connected through a noise filter to the junction point of the two bridges, and the other side of the external load is connected to the center tap of the fixed voltage source. The output power ports of each converter drive the primaries of their respective converter transformers. The effective turns ratio between primary and secondary windings of these converter transformers determine the voltage/current step-up/step-down relationships between the tubes and the external load impedance.

27 Claims, 2 Drawing Sheets



No power gain in the impedance matching process.

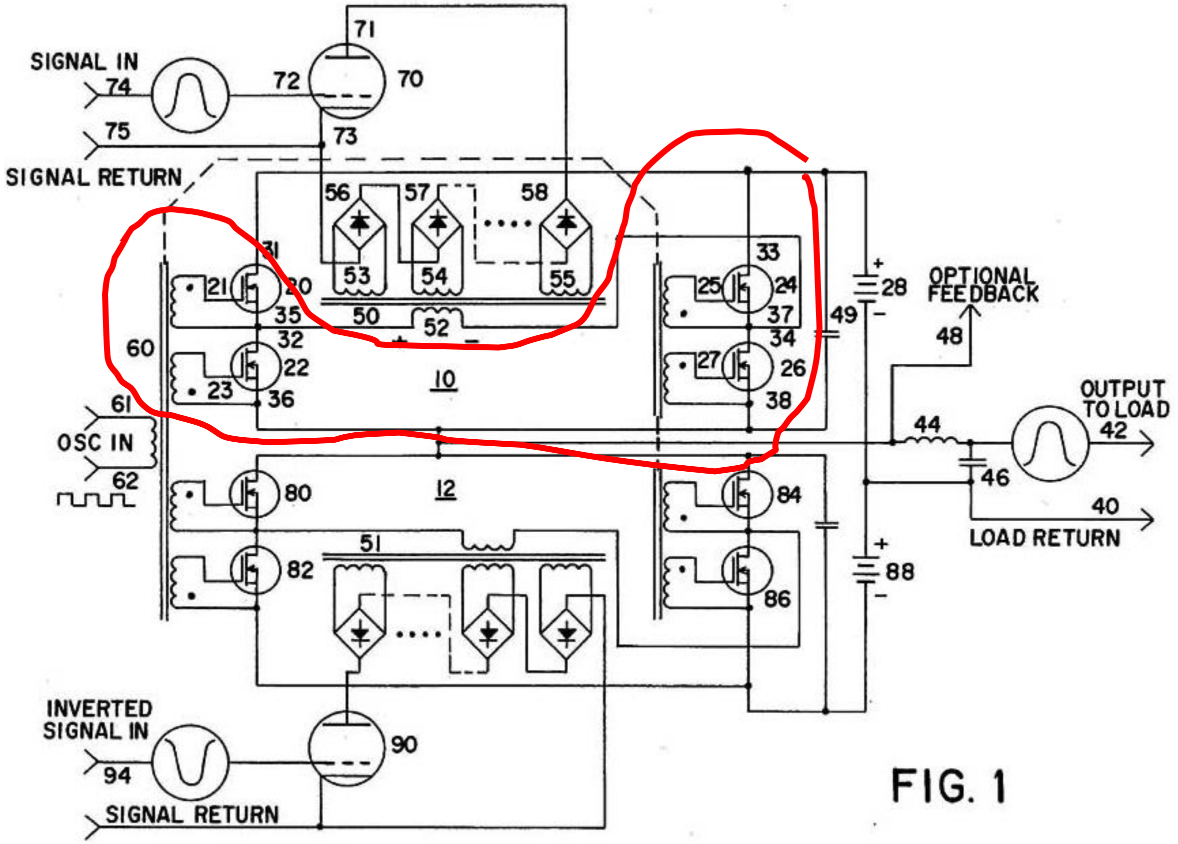
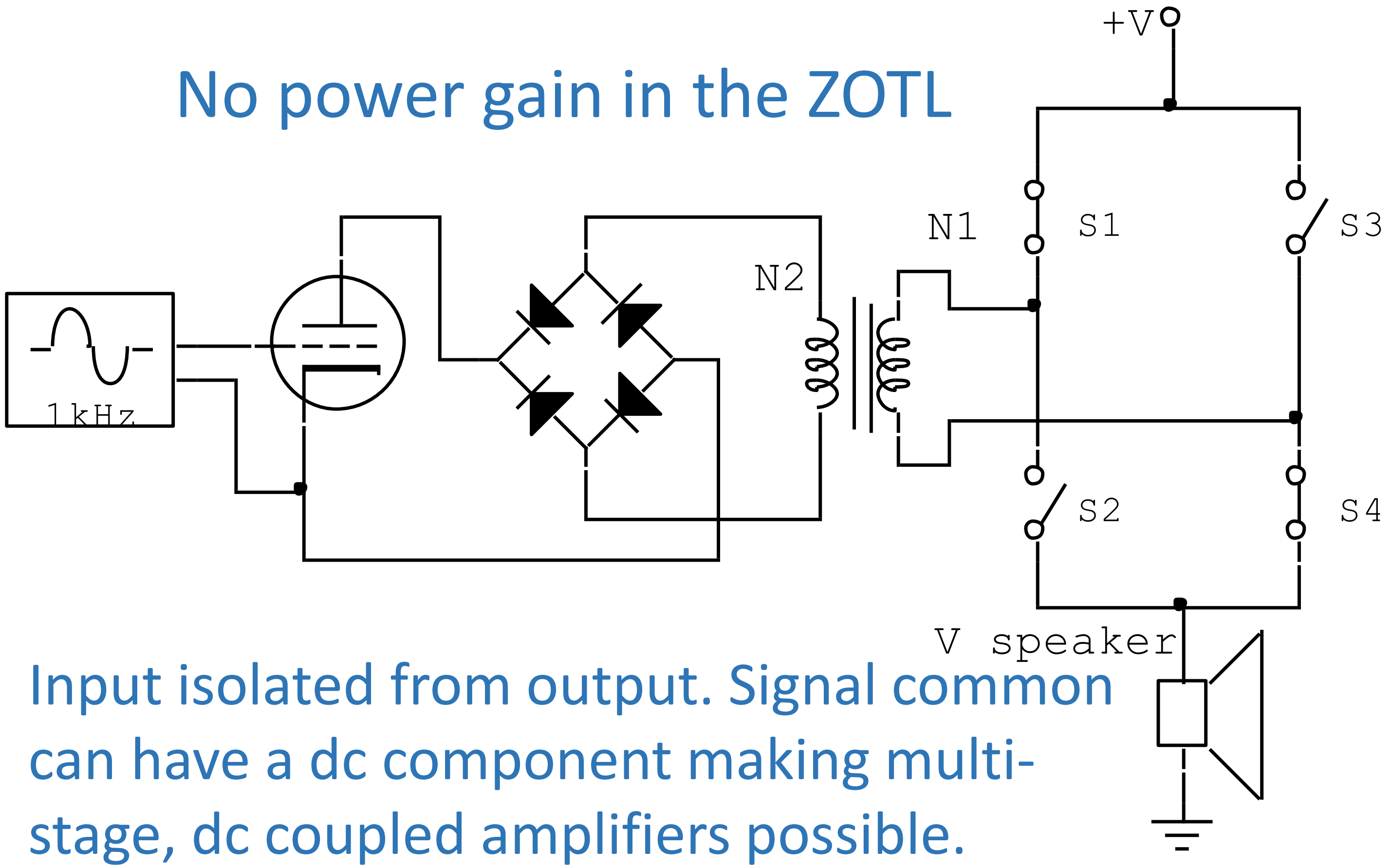


FIG. 1

How the tube controls the speaker in the ZOTL

No power gain in the ZOTL



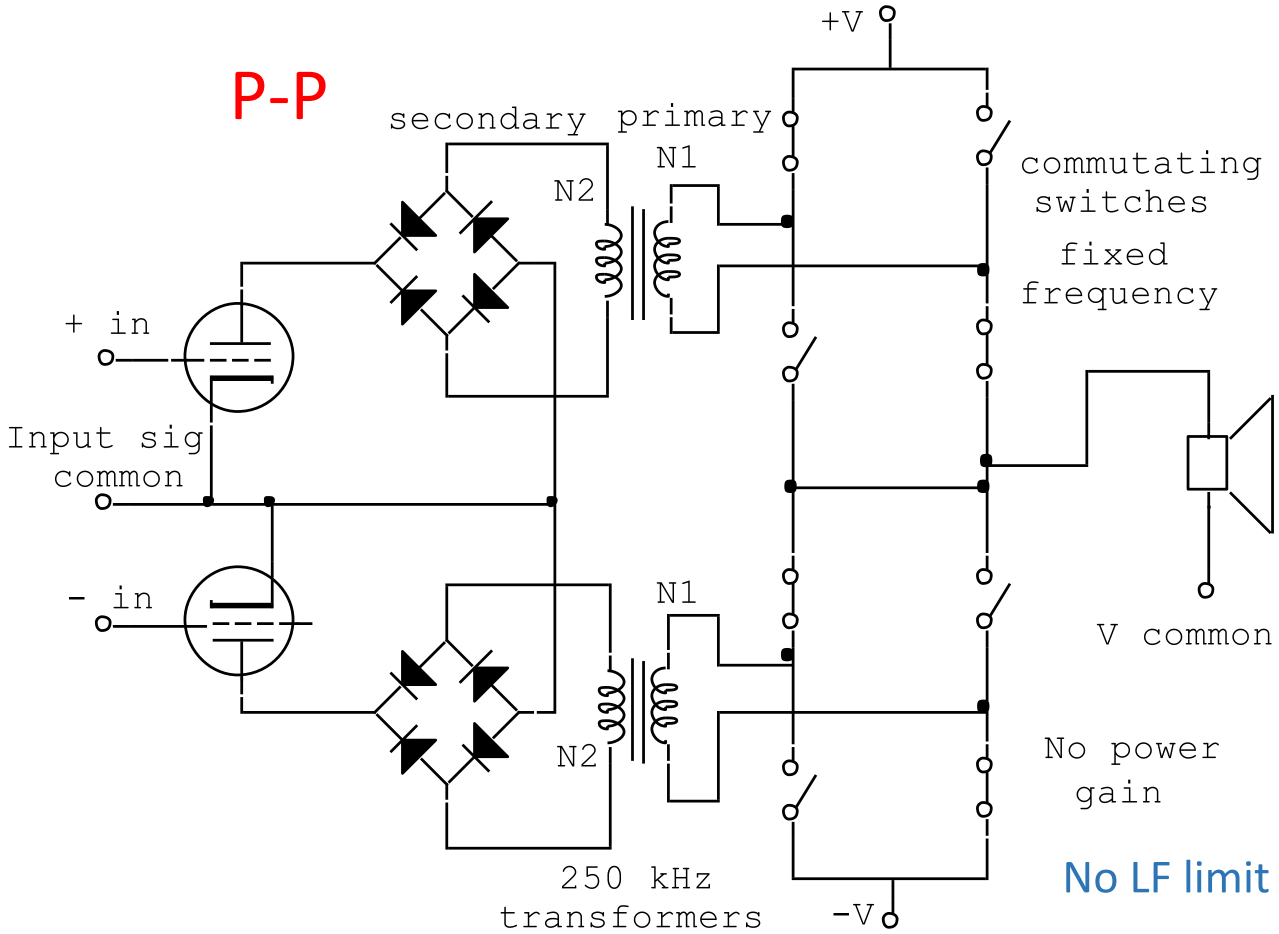
Input isolated from output. Signal common can have a dc component making multi-stage, dc coupled amplifiers possible.

Note that the +V voltage supply is applied to the series combination of commutating bridge and the speaker. So only the portion of +V across the bridge is modulated and applied to the primary of the transformer. The remainder is unmodulated and applied to the speaker.

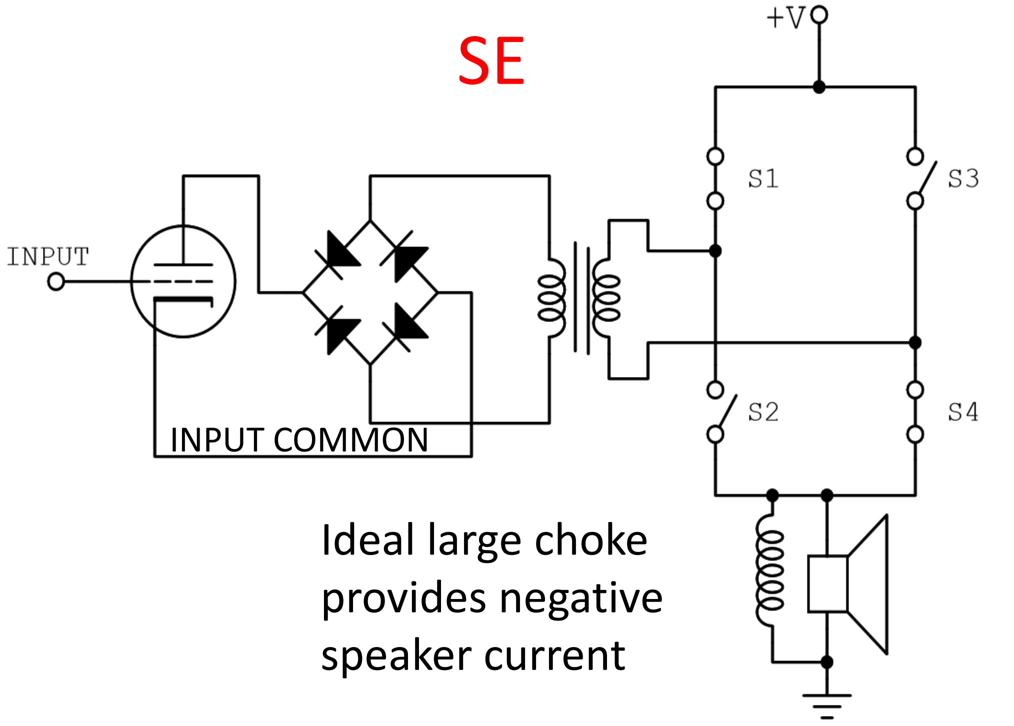
The plate-to-cathode voltage on the tube is (+V)-(Vspeaker) (N2/N1), now demodulated via the rectifier bridge.

As the conductance of the tube is modulated by the audio signal, the conductance of the MOSFET commutating bridge changes accordingly by loading through the transformer. This modulates the audio-frequency voltage applied to the speaker.

P-P

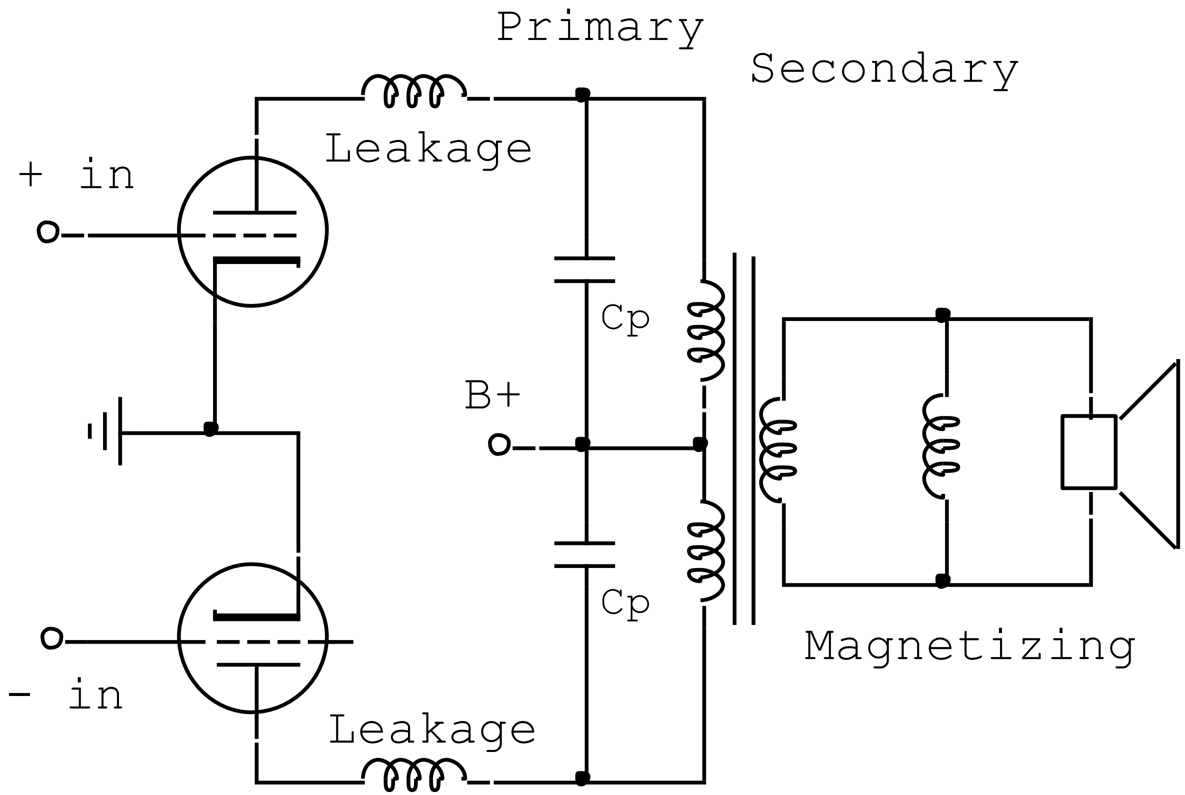


SE



Energy-storage function, Size determines LF limit

For non-ideal chokes a small negative dc voltage must be applied to the choke instead of grounding to account for the dc resistance of the winding. This will make the dc voltage across the speaker zero for no-ac signal conditions but with a dc-idle current in the tube.



OUTPUT TRANSFORMER,
including parasitic elements

Let's Review

- Matches high tube voltage/impedance to low speaker voltage/impedance.

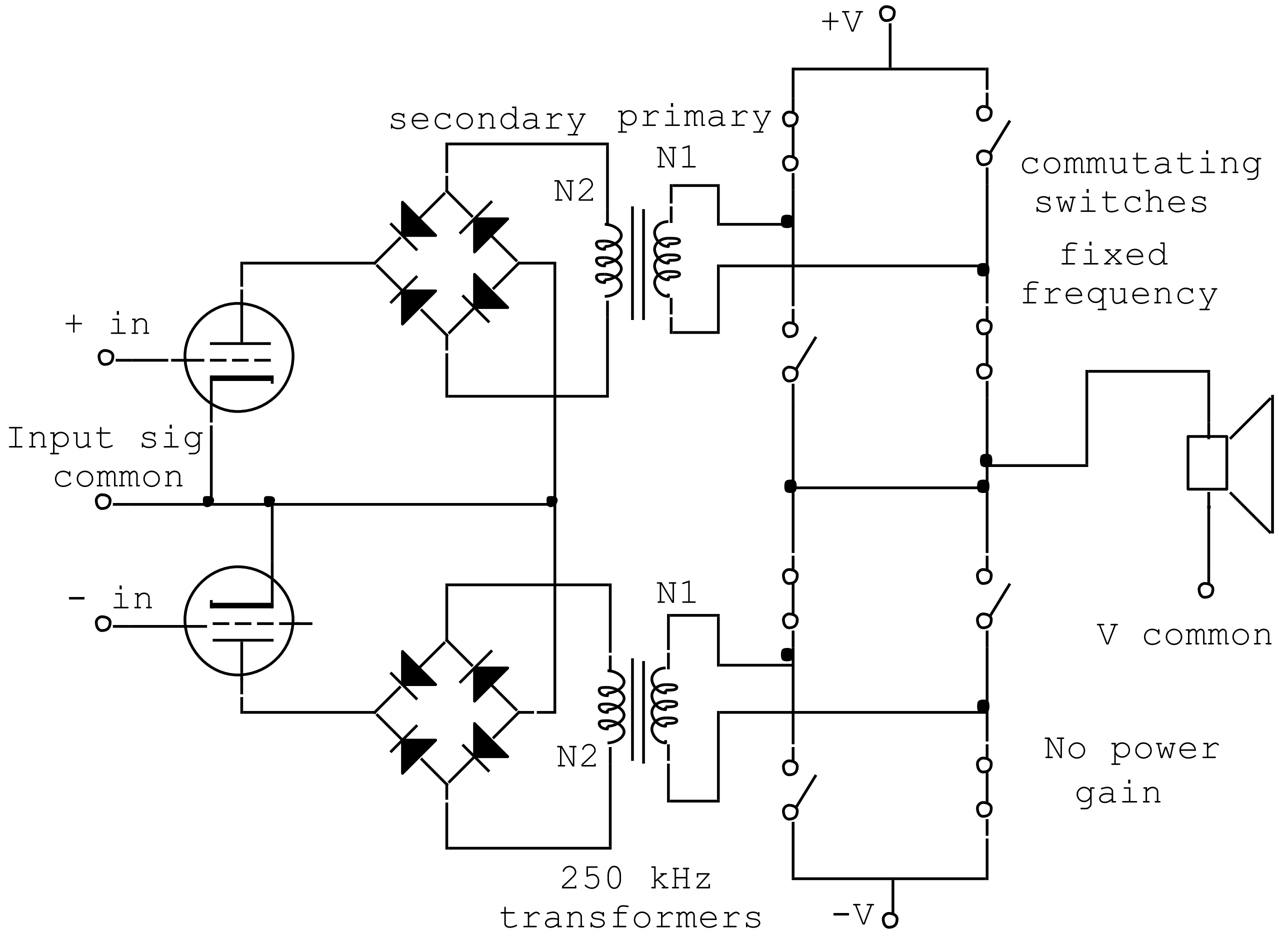
- Power fed into system from primary side, with tubes, at high voltage.

- Bandwidth limited at high frequencies by leakage inductance and parasitic capacitance in transformer.

- Low frequencies limited by magnetizing current and saturation.

- Parasitics reduce the amount of feedback that can be applied to lower distortion and output impedance.

- Simple ac-coupling concept.



ZOTL- Transformer parasitics not shown but similar to output transformer. Parasitics effect efficiency in both positive and detrimental ways but do not affect frequency response.

Differences

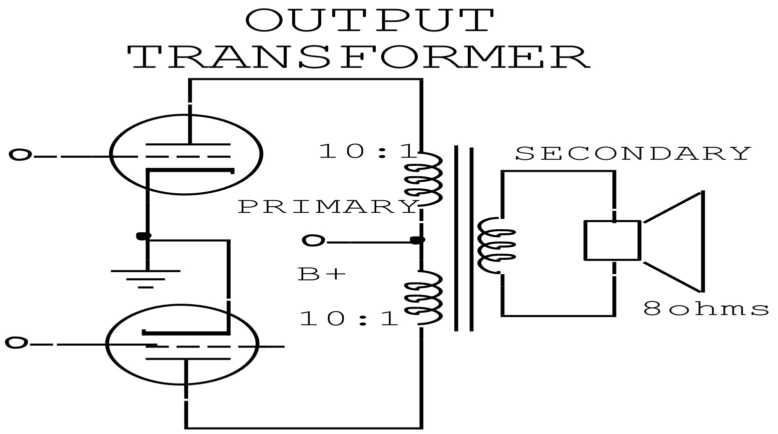
- Power fed into system from speaker side (now primary) at low voltage.

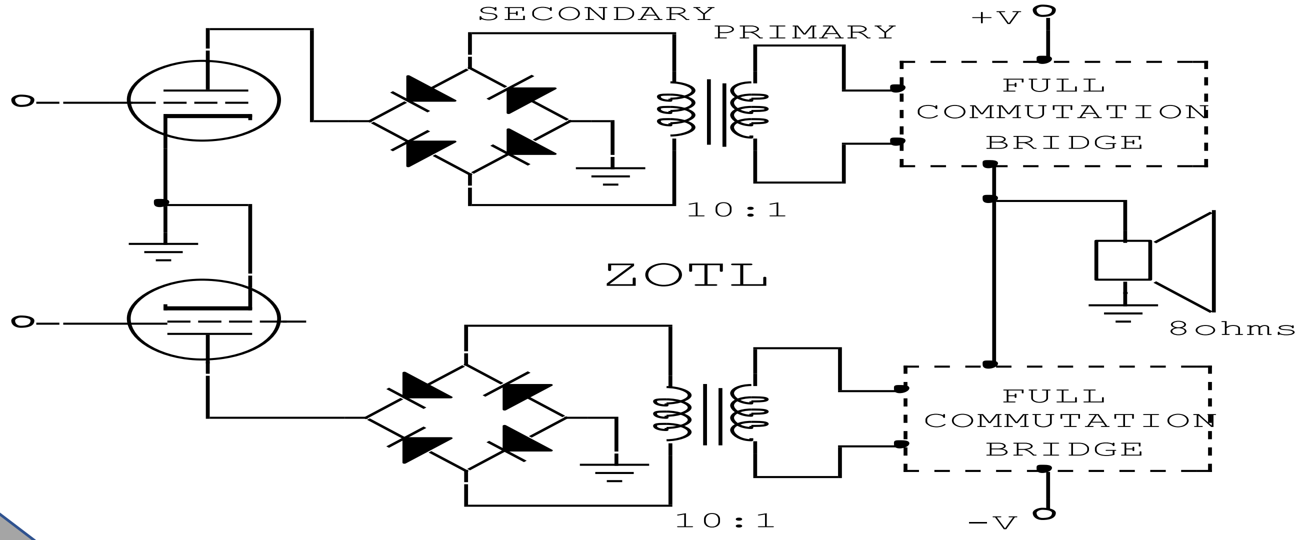
- High-frequency bandwidth limited by optional noise filters.

- No low-frequency limits.

- Dc to dc power conversion concept.

REFLECTED IMPEDANCE



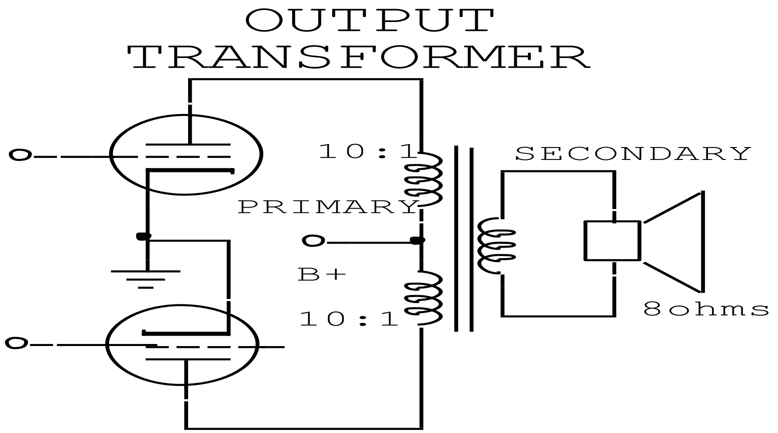


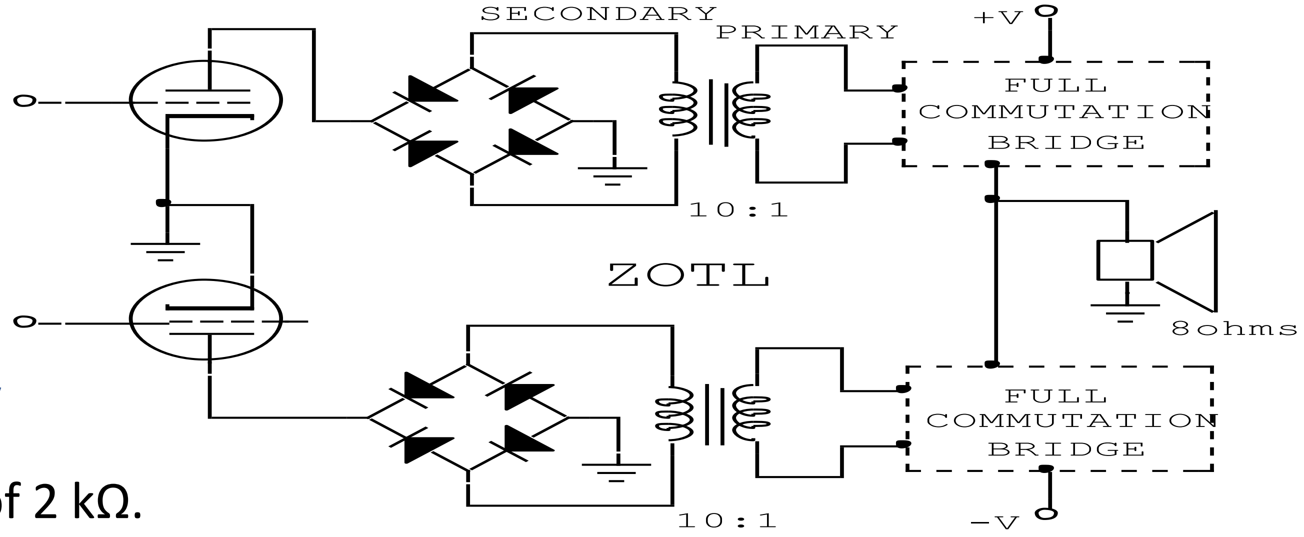
Overall turns ratio 10:1 + 10:1

So overall 20:1 plate to plate

- Impedance goes as the square of the turns ratio so impedance conversion is 400.
- The 8-ohm speaker presents 3200 Ω to series-connected tubes plate to plate.
- But the speaker presents 800 ohms to one tube at a time under class B large-signal conditions.
- Suppose each tube has a plate resistance of 2 kΩ.
- Each tube reflects 20 Ω to the speaker through half of the transformer.
- Under small-signal conditions tubes can be treated as being in parallel and the reflected impedance to the speaker is 10 Ω.

REFLECTED IMPEDANCE



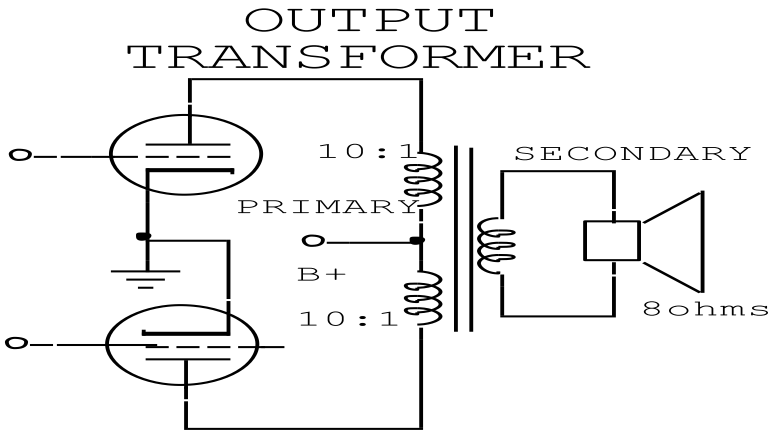


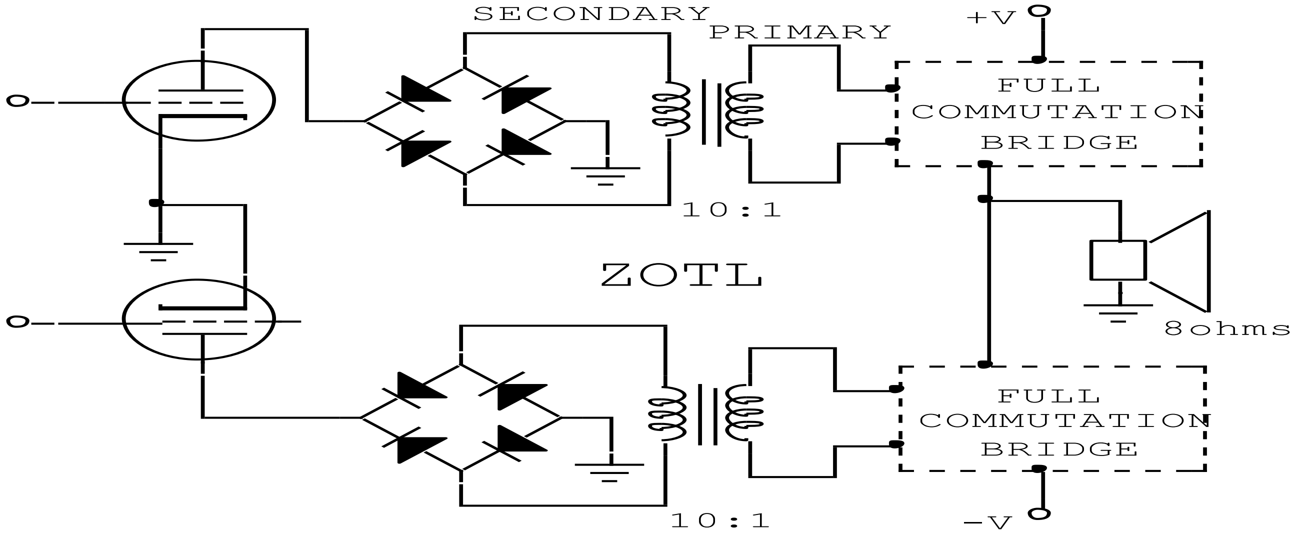
Suppose again each tube has a plate resistance of 2 kΩ.

- Each tube reflects 20 Ω to its respective full-bridge MOSFET commutation set.
- But the total reflected impedance to the speaker is 10 Ω because under ac-small-signal standpoint the two MOSFET bridges as well as the tubes are in parallel to ground.
- Under large-signal conditions for class B, one tube is turned off and its respective MOSFET bridge presents an open circuit.
- Then the 8-ohm speaker presents an 800-ohm load to the one active tube through the active MOSFET bridge.
- Under small-signal conditions the 8-ohm speaker presents 3200 Ω plate to plate with overall impedance conversion of 400.

Note that when plate-to-plate configuration terminology is used, the two tubes are in series as far as loading. Thus each 2 kΩ tube adds to make 4 kΩ with overall conversion of 400, resulting in a 10-ohm source impedance at the speaker like we had before.

REFLECTED IMPEDANCE





To summarize, in the ZOTL under small-signal conditions, the primaries of the converter transformers are in parallel and the secondaries are in series. The commutation bridges become part of the primaries and the bridge rectifiers become part of the secondaries. Thus the ZOTL becomes identical to the output transformer for the treatment of reflected and transmitted impedance. Only the names primary and secondary switch places as power is fed to the system on the primary side.

The commutation bridges do not act like buffers. The tubes see and react to any impedance variations with frequency that the speaker presents, same occurs with an output transformer.

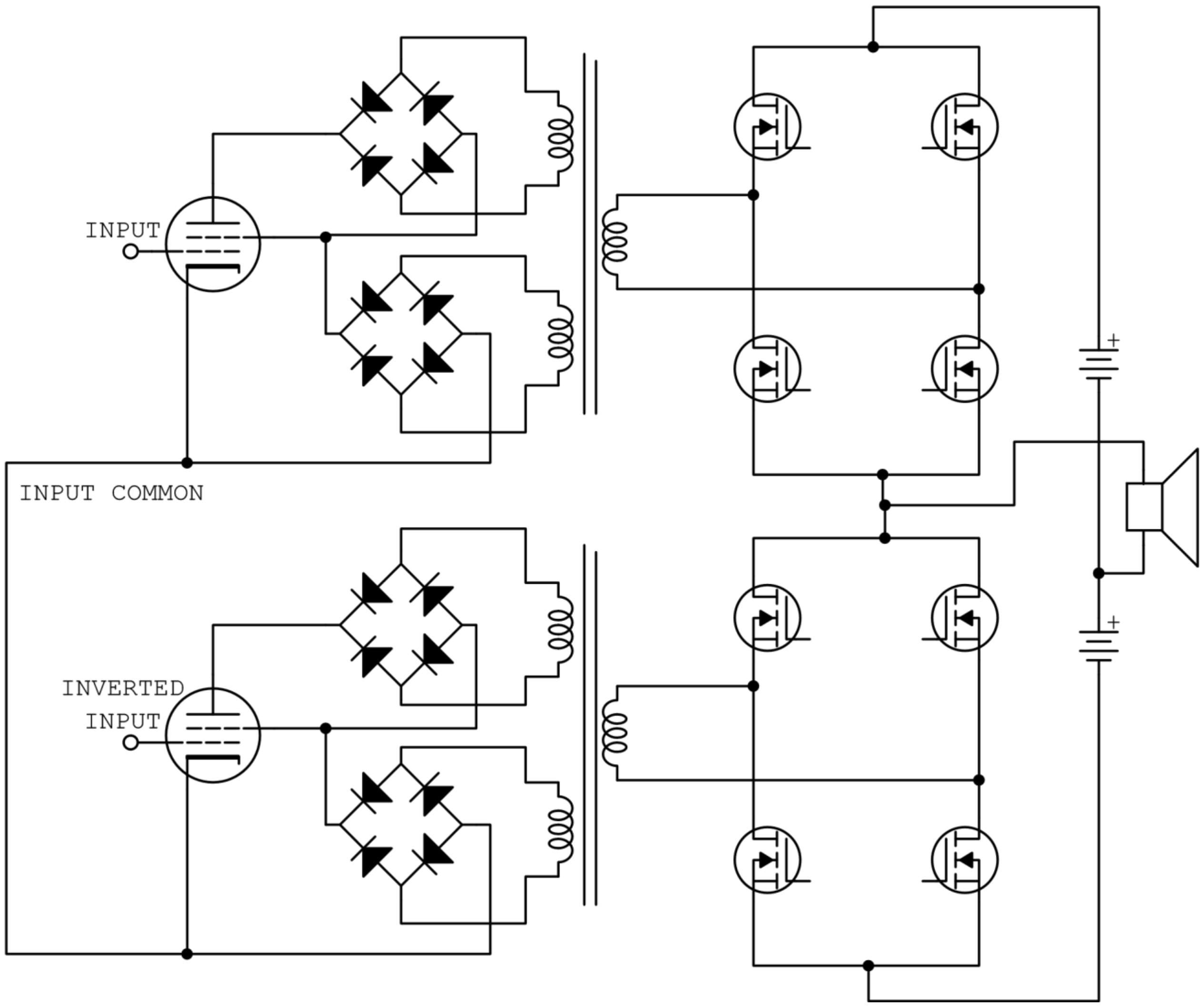
Additional Differences Not Related to Normal Audio Reproduction

- ZOTL will not impedance match a signal with the same frequency as the carrier frequency.

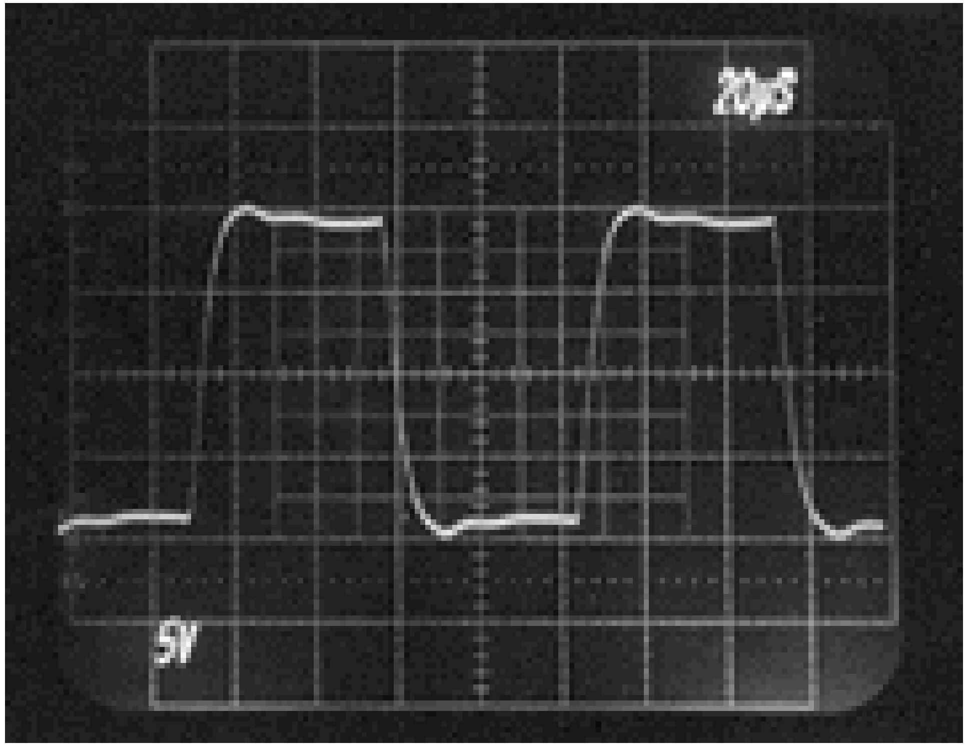
- Minor signal amplitude variations are present if those signals are harmonically related to the ZOTL switching frequency.

- ZOTL *will* impedance match signals higher than the switching frequency, unlike a digital system or most carrier systems.

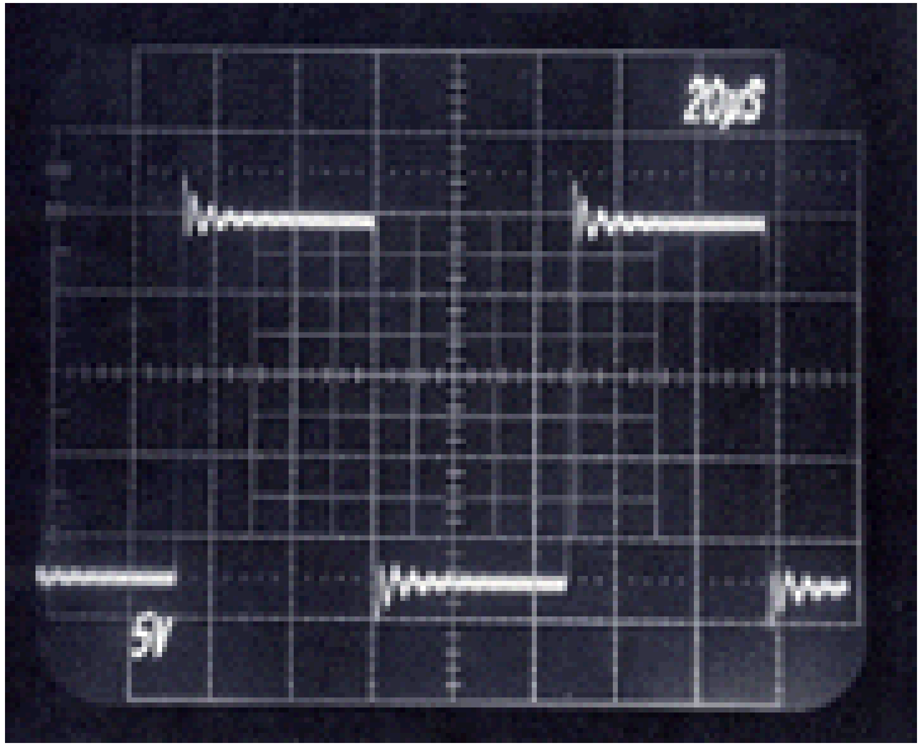
ZOTL Ultra Linear implementation. A portion of the plate voltages, both ac signal and dc is fed to screens of tubes. Like the output transformer this is local feedback that lowers output impedance and distortion. Unlike the output transformer that applies nearly the same dc components to both the plates and screens, the dc components scale with the ac components in the ZOTL. This feature allows a higher plate voltage because the screen voltage rating is limited in many tube types.



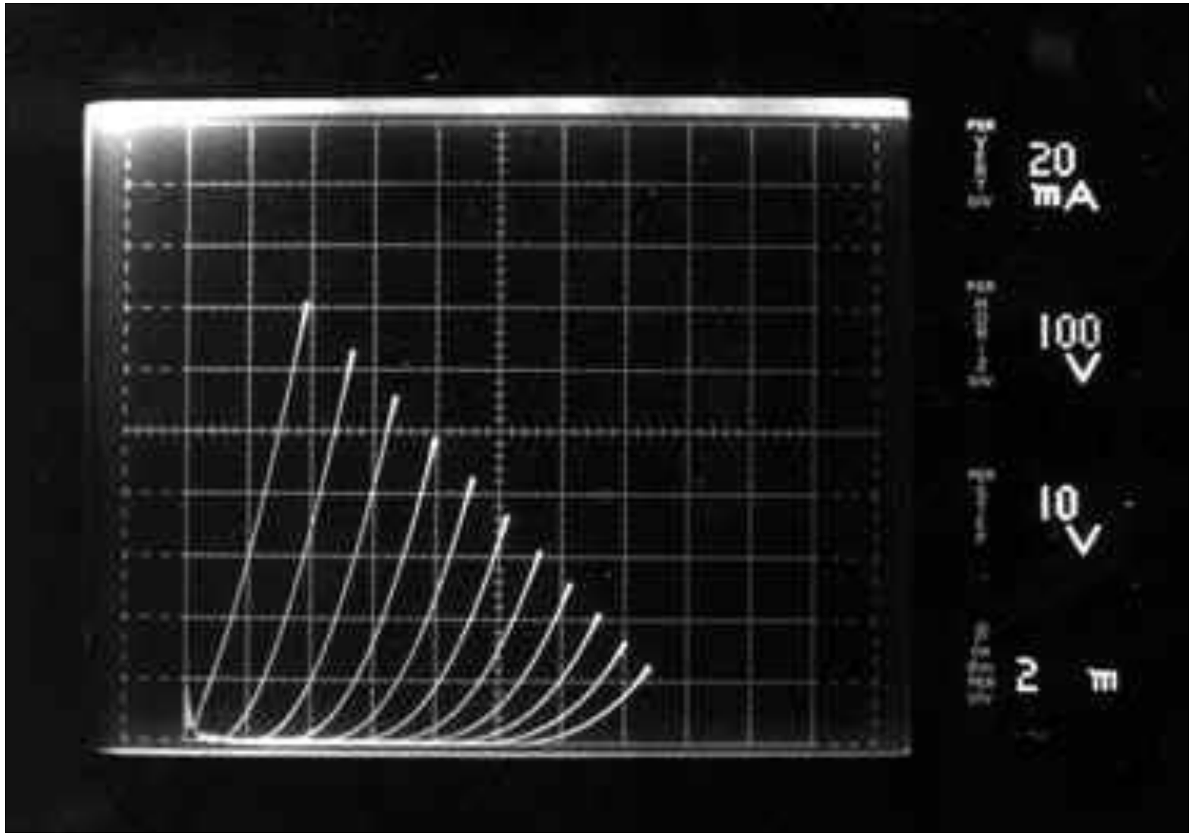
P-P shown, works with SE



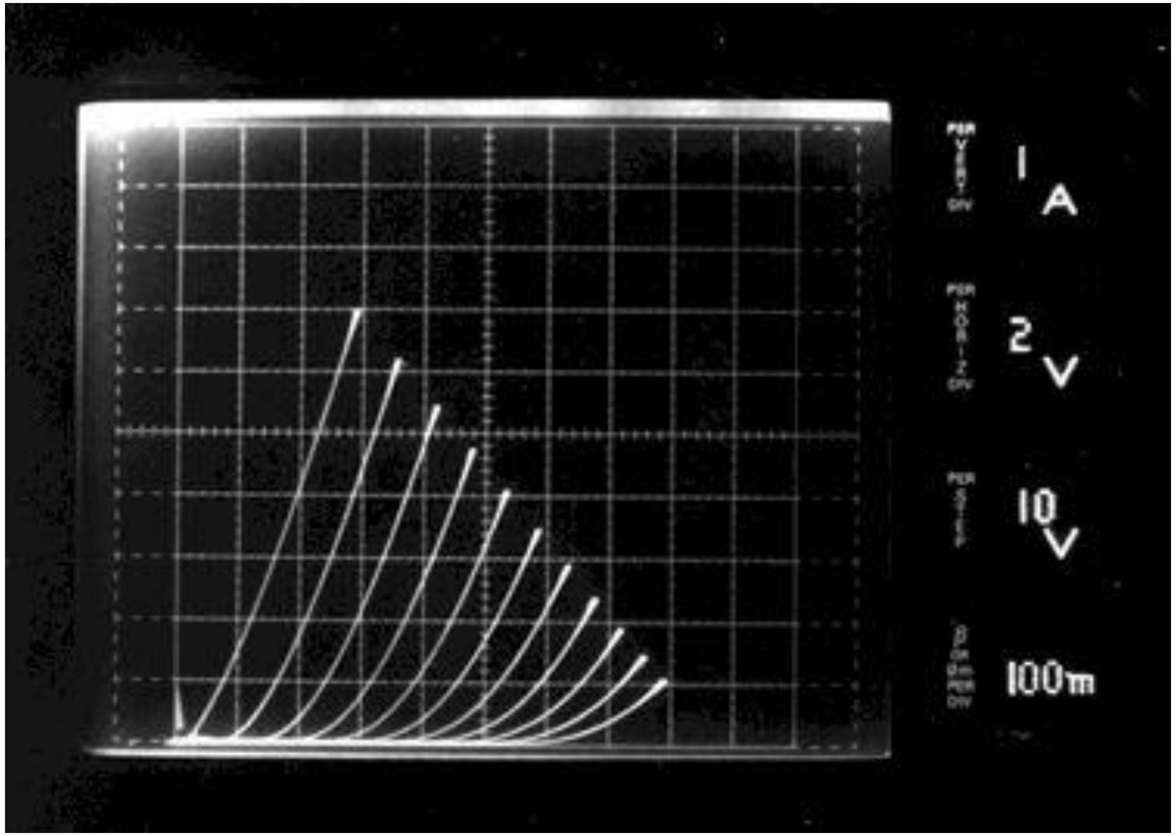
Audio Output Transformer- 10 kHz.



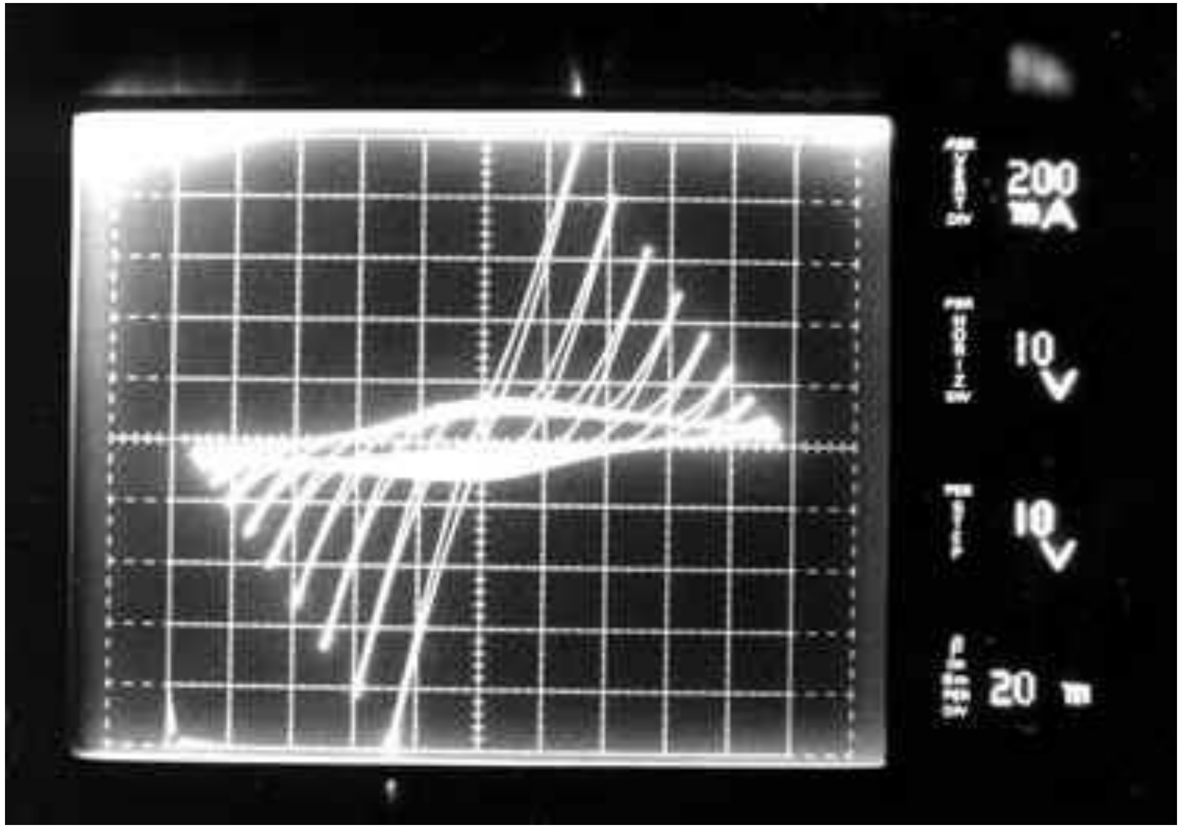
ZOTL Impedance Converter- 10 kHz.



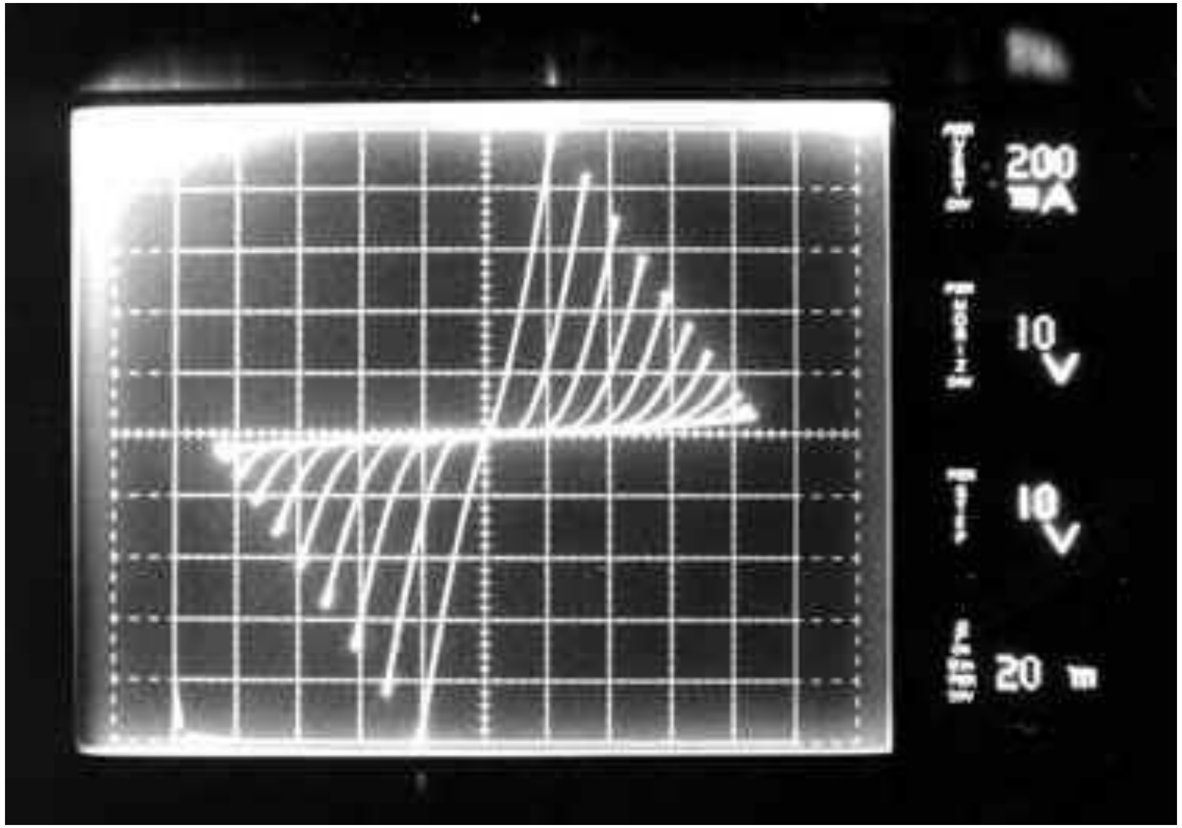
Transfer characteristics of a triode-connected 6L6.



Triode-connected 6L6 curve traced through the ZOTL impedance converter.



Push-pull pair of 6L6s, triode-connected, and curve-traced through an output transformer.



Push-pull pair of 6L6s, triode-connected, and curve-traced through the ZOTL impedance converter.

200-watt Berning ZOTL

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