AmpDiVa White Paper

On the use of vacuum tubes as switching devices in Class-D power audio amplifiers

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By the means of a suitable grid polarization technique and connections through controlled impedance and length equalized transmission lines, vacuum tubes can be used as power switching devices in Class-D power audio amplifiers in *full-bridge* and *half bridge* configurations.

Preamble

Since several decades, all the tube data sheets depict only their working region at negative polarized grid (for example [1]).
At the beginning of the history of the electronic engineering, in text-books (for example [2]) triodes were described by considering also the working region at positive polarized grid.
Still during the 1900's sixties, we can find some rare, and may be latest, description of positive grid polarization [3].

Positive grid polarization

Regarding to the triode operation, nothing prohibits that the grid could be polarized with a positive voltage related to the cathode instead of a negative voltage.
With the usual negative polarization, the grid current is negligible and the triode acts like a Field Effect Transistor.
With the positive polarization, the grid current rises noticeably at the rising of the grid voltage as the grid is operating now as the anode of a vacuum diode in direct conduction.
Anyway in this condition the grid is still working as the triode anode current regulator and the anode V-I characteristic figure becames really interresting, with high anode saturation currents at low anode voltages in the order of few tens Volt.
The triode is now operating like a Bipolar Junction Transistor, with a non-zero grid current and the anode-cathode circuit acting as an equivalent current generator controlled by the grid voltage (in the BJT the emitter-collector current generator is controlled by the basis current).
Furthermore, the use of a low anode voltage achieveable with the positive grid polarization means a low negative grid voltage is enough to drive the triode in the off-state reducing to zero the anode current (fig.1).

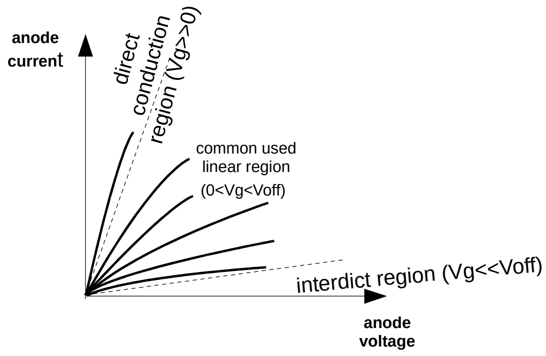

fig.1 – V-I anode figure extended to the positive grid polarization region

Use in switched bridge circuits

The availability of a suitable grid driver circuit which from a binary input provides a bipolar output respect to the cathode (fig.2), allows to use a triode as an electronic switch (fig.3).

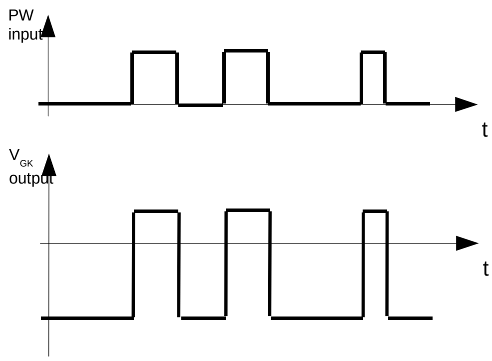

fig.2 – Grid driving by bipolar pulses

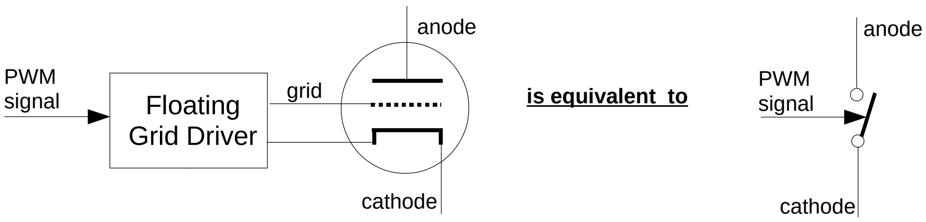

fig.3 – Functional equivalent circuit of a triode driven by a bipolar floating grid driver circuit

If the grid driving circuit is floating, with its own power supply and its input insulated by the means of, for example, a pulse transformer, an optocoupler, condensers or an optical fiber link, then two triodes can be connected in “half-bridge” or four in “full-bridge” configuration.

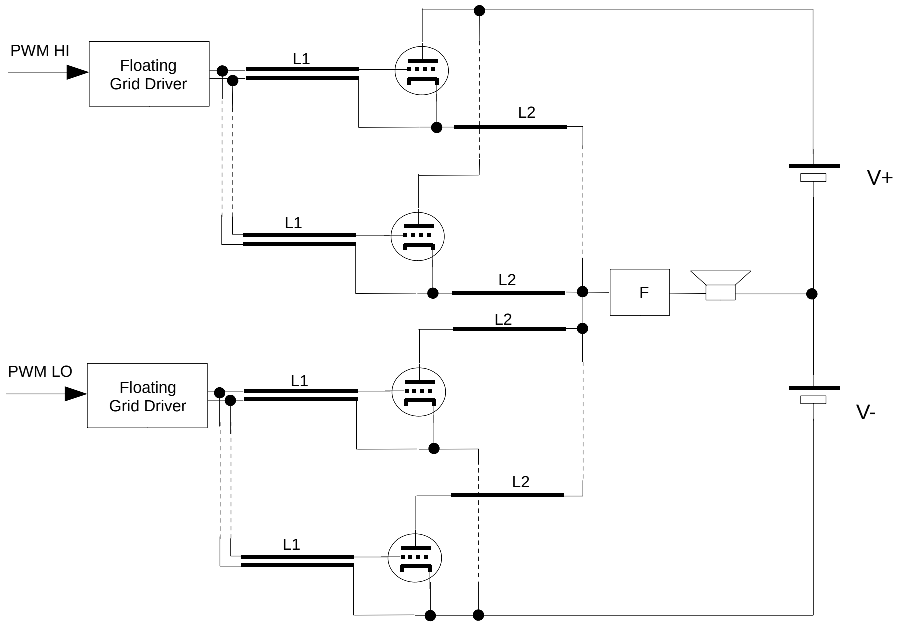

fig.4 – half bridge class-D power amplifier based on vacuum tubes as switching devices (F output filter, L1, L2 equalized and impedance matched transmission lines)

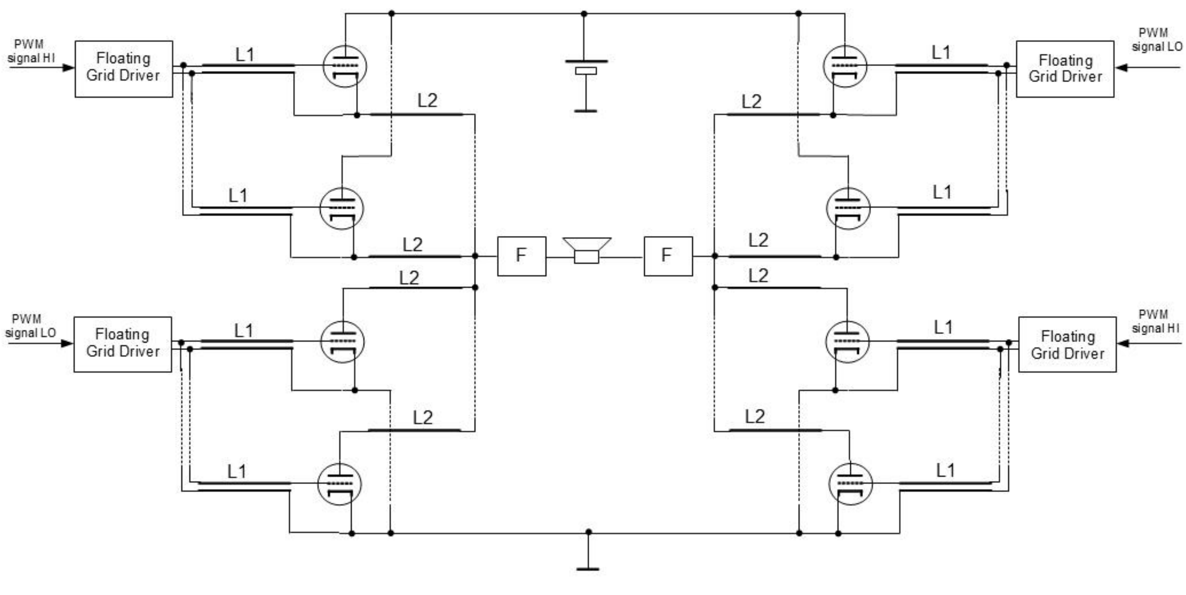

fig.5 – full bridge class-D power amplifier based on vacuum tubes as switching devices

As it is depicted in fig.4 and 5, in order to increase the bridge output current, it is possible to connect in parallel several triodes in each bridge arm, having designed the grid drivers with enough output current to drive all the grids of every arm.
The triode parallel connection decreases the bridge output impedance allowing, thanks also to the low anode voltage requirement, the direct connection to a low impedance load as the loudspeaker without the need for any output transformer.
In the positive grid on state, the triodes work as current generators and the anode current becames load indipendent; due to this property, the output power at the load increases as the load impedance

increases.
For example, using as a load three loudspeakers connected in series, the output power will be triple respect the use of a single loudspeaker.

These kind of circuits can be also developed with penthodes or other multi-grid tubes, having the other grids connected in a way to obtain an equivalent triode.

About the switching speed
In classic linear amplifiers at high frequencies the interelectrodes spurious capacitances act as bandwith reduction elements.
In linear amplifiers tubes with spurious capacitances of the order of few tens pF are only suitable for audio circuits, as they can not be used in radio frequency applications.
Driving the same audio tubes in switching mode with positive grid, the effect of these capacitances is only in the reduction of the maximum slope speed at the edges of the switching signals.
Audio application specific triodes (with relative high spurious capacitances) can provide edges within the tens nanoseconds range, allowing the bridges to operate at several hundreds KHz switching frequency.

These results can be achiede if the triodes are connected by the means of matched impedance transmission lines, whose control the signal edge distorsions avoiding the effect of signal reflections along the line.
The lines have also to be lenght matched in order to provide the same propagation delay for each signal edge coming from the grid drivers to the triodes or from the triodes to the load output.

References
[1] Philips, (1970), *ECC83 data sheet*
[2] Ulivo, A. (1926), *Radiotelefonia*, G. Lavagnolo ed., Torino, 89.
[3] Malatesta, S. (1967), *Elettronica e Radiotecnica vol. I*, Colombo Cursi ed., Pisa, 154.