10.5.3 Push-pull class-B operation

In a push-pull class-B amplifier, the operating point is not positioned in the middle of the load line but at its lower end. Without a drive signal, only a small idle-current flows though the power tubes. There is lesser load on the power supply and the tubes do not get as hot – however the obtainable output power is still higher than that of the push-pull class-A amplifier.

To keep the plate current small while there is no drive signal, the **grid bias voltage** needs to be on the rather negative side. Due to the small current, this cannot be achieved as a voltage drop across a cathode resistor anymore, and therefore both cathodes are set to ground potential while a separate DC voltage-source generates the required negative bias-voltage (measuring, after all, in the order of -15 … -65 V) at the grid. This DC voltage-source is designated U_{g1} in **Fig. 10.5.10**, and it is fed to the circuit via two high-impedance resistors (e.g. 220 kΩ) connected across, and two grid resistors (e.g. 1 … 5 kΩ; there are circuits without these grid resistors, as well).

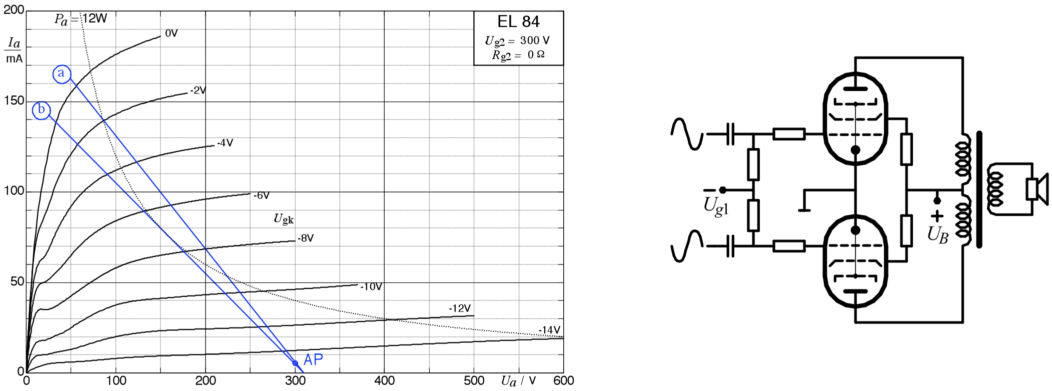

Fig. 10.5.10: Output characteristics of the EL84; circuit of the push-pull class-B power stage.

We obtain the optimum gradient of the load line (and thus the optimum **load impedance**) if the intersection of the $U_{gk} = 0$V-characteristic and the load line has the maximum distance from the operating point. **Fig. 10.5.10** shows two different load lines: the flatter line (b) relates to a 2.0-kΩ load-impedance while for (a), the load-impedance is 1.6 kΩ. It is of no issue that the hyperbola designating the power limit is intersected: the tube is only subject to strain during one half-wave, and the plate dissipation remains within the tolerable limit on average. Static drive signals, or drive signals of extremely low frequency are not to be expected with guitar amplifiers since the power stages are fed via a high-pass.

The maximum **power** yield does not differ much between the two variants: it is about 19 W for (a), and 18 W for (b). As a comparison: a corresponding push-pull class-A power stage could only deliver about 11 W. Besides the maximum power yield it is, however, also the power required from the power supply that merits consideration, especially in the case when there are small drive signals. For the push-pull class-A power stage, the load on the power supply is independent of the drive level, e.g. 24 W for 2xEL84. In contrast, the power supply needs to deliver as little as 3 W in the push-pull class-B power stage (depending on the bias setting). **Fig. 10.5.11** shows the power balance – albeit without considering the power dissipated in the screen grid that would amount to about an additional 3 W at full drive levels. In the class-B mode, the output power is larger and the power losses in the tubes are smaller: the maximum plate dissipation in class-B mode is only about half of that found in class-A mode.

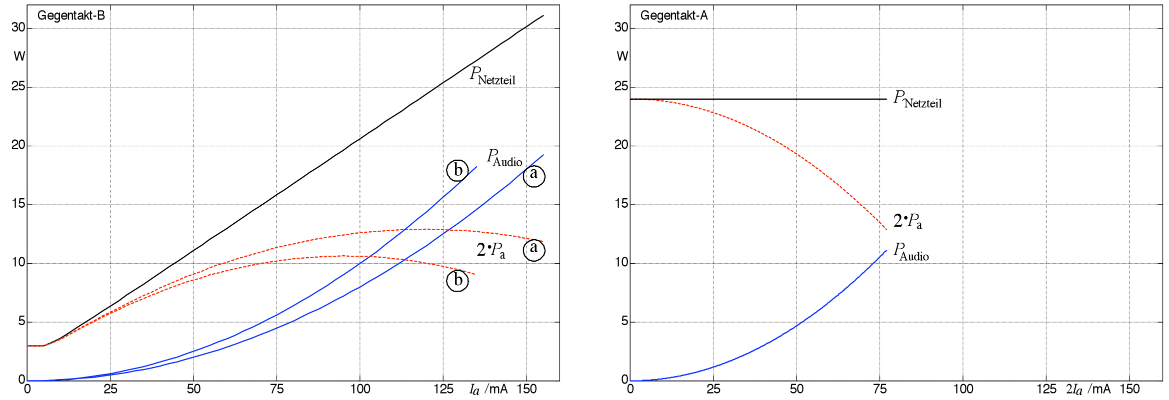

Fig. 10.5.11: Link between power-supply load (without g$_2$-dissipation) and output power P_{Audio}. "Gegentakt" = push-pull. The difference between the two curves corresponds to the plate dissipation $2{\cdot}P_a$ of both tubes. (U_B = 300V).

The relatively high efficiency of the push-pull class-B circuit results from the fact that each tube carries a large plate current only when power is actually delivered to the load. For this, the operating point needs to be set at the lower end of the load line. However, the bias-voltage at the grid must not become too negative because this would result in **crossover distortion** (**Fig. 10.5.12**). Given a sufficiently large bias-current (left-hand section of the figure), the two tube characteristics superimpose to a reasonably smooth curve, while for too small a bias-current a saddle point appears (middle and right-hand sections of the figure). This saddle point will increase the odd-order distortion on one hand, and on the other hand leads to an undesirable (progressive) drive-dependency of the slope of the characteristic (Chapter 10.5.8). Special consideration needs to be given to the fact that the supply voltage decreases with increasing drive levels – the **screen-grid voltage** therefore decreases as well, and this further emphasizes distortion (Chapter 10.5.8).

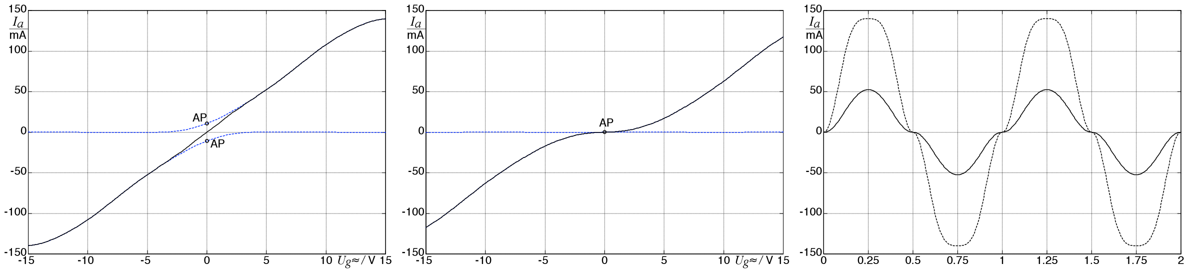

Fig. 10.5.12: Characteristics at different bias-current settings. Crossover distortion. On the right, the distortion relating to the middle picture is depicted for two different amplitudes.

Literature does **not** give an **exact definition** for the load line in push-pull class-B operation. Rather, it mentions "small plate-current", and occasionally even a plate-current for which the operating point is set "almost to zero". This did not keep Siemens and other tube manufacturers from specifying a bias current for the EL34 of no less than 35 mA. They do have a point because the theoretical case that the plate-current approaches "almost zero" has next to no bearing on low-frequency applications. 35 mA: that is indisputably "somewhat more than almost zero", and whether this mode of operation may in fact be still called "push-pull class-B" is subject of controversial discussions. Alternatively, the term "push-pull class-AB operation" is used, or the term "push-pull class-D operation" – it is important to know that these designations are ambiguous! (Details are found in Chapter 10.5.4).

In class-B operation, the two power tubes conduct simultaneously only for small drive levels; at higher drive settings each power tube conducts predominantly only during one half-wave. This needs to be taken into account when choosing the **cross-section of the wire** in the transformer. If we assume a sinusoidal drive signal, and a **peak plate-current** of 141 mA (Fig. 10.5.10), the RMS-value is not 100 mA but only 50 mA.

The **plate-voltage** without drive signal is, for class-B operation, just slightly less that the supply voltage U_B (e.g. 300 V). During the half-wave at which the tube is conducting, the plate-voltage drops as far as the residual voltage (e.g. 30 V). During the other half-wave (blocked mode), the plate-voltage does not remain at the level of the supply voltage but increases to almost double of that value (e.g. 570 V!) This is because the primary winding of the output transformer sees practically no load when the respective tube is in blocking mode, while the magnetic flux generated by the other (active) tube induces a high voltage in this winding without load. In power stages that operate with higher supply voltages, voltages that are even much more dangerous can result: e.g. 850 V in Fender amplifiers, or 1100 V in Marshall 200-W-amps. These high voltages are not contradictory to the information given by datasheets where the maximum plate-voltage is specified e.g. at 800 V; the values expressed there are meant as idle voltage (without drive signal). For example, the datasheet of the EL34 determines the maximum plate-voltage at 800 V but allows for maximum peak voltages of 2000 V in the blocked mode. Such high voltages can in fact occur easily if the amplifier is not connected to its nominal load but operated with a higher impedance, or no load at all at the output. In this case, spark-over or arcing between the connector-pins 3 and 2 (plate and heater filament) can easily happen – which is likely to damage the tube socket and/or the tube holder irreversibly. Even more dangerous is an insulation-destroying spark-over within the output transformer because an adequate replacement for this component may not be at hand.

A few comments regarding seemingly “useless” circuits-components: that they are included often needs to be credited to practical insights. The grid-resistors (2 – 5 kΩ) connected in series with the (apparently high-impedance) control grid will reduce the tendency of a power stage to self-oscillate. High-frequency self-oscillations may occur – but they do not have to. The power stage may well operate perfectly without these resistors, as well; however, it is advisable not to simply omit them. With each tube- or loudspeaker-change, different stability-criteria creep in, and the small additional investment for these resistors can very quickly pay off. The same holds for small capacitors (10 – 100 pF): if they are not directly connected to the tone-filter stages, they presumably are supposed to suppress RF-oscillations. It is indeed possibly that they were (had to be?) chosen with a value that audibly cuts into the brilliance of the guitar sound. If that is the case, we find a wide field of possibilities to improve the sound – but we are also confronted with a good chance that we operate a powerful radio-transmitter as we change or remove such capacitors. Since power-stage oscillations can easily occur in the FM-range (100 MHz), it is recommended to check the stability with a broadband oscilloscope. Evidently, we must not discard such oscillations as “inaudible” and therefore irrelevant: on one hand, operating such a transmitter may be unlawful, and on the other hand the power tubes may be overloaded massively. Moreover, there may well be secondary symptoms that are audible.