10.5.7 Internal impedance of the power stage

Tube circuits are of high impedance while loudspeakers have a low impedance. The output transformer – with the term "matching" appearing in its description – serves as mediator between these different impedance levels: indeed, the output transformer *matches* the different impedance levels *to each other*. Usually, the term "matching" indicates that source- and load-impedance are of equal magnitude. For a tube amplifier, this would mean that its internal impedance is decreased to the level of the loudspeaker by the output transformer, i.e. is brought down to e.g. 8 Ω. This strict definition of the term "**matching**" should, however, not be used in the context of tube amplifiers; the impedance levels are brought closer to each other, but they are not actually (power-) matched. In a tube amplifier specified for a nominal loudspeaker-impedance of 8 Ω, the internal impedance of the amplifier (the source impedance) will normally not be 8 Ω but much more, e.g. 100 Ω. Tube amplifiers operate "almost as current sources", and not with power-matching.

For HiFi-loudspeakers, such a current imprint is usually unwanted because an emphasizing of the loudspeaker resonance will result. Customary is the operation from a source with very low impedance that reduces the undesired high Q-factor [3]. This ideal can be achieved almost perfectly with transistor power-stages, while in tube power-stages, the impedance can be reduced via negative feedback – but not to the same degree as in transistor amplifiers (phase-shifts, tendency to self-oscillate). The question whether **negative feedback** is at all desirable in **guitar amplifiers** has received quite different answers in the past: no negative feedback in almost all VOX amplifiers and very early Fender amps; inclusion of negative feedback in almost all Fender amps from the early 1950's. The amplifier with NFB reacts "more civilized" with lower non-linear distortion compared to its feedback-free counterpart – at least as long as it is not overdriven. Whether the lower distortion is felt to be an advantage is a matter of taste and shall not be the subject of an evaluation here. However, since the negative feedback does not only influence harmonic distortion and dampening of the loudspeaker, but also has an effect on the source impedance of the guitar amplifier, another question becomes obvious: can the **output power** be increased via negative feedback? The NFB as we see it in power stages does decrease the ("too high") internal impedance of the amp – it should be possible to interpret this aspect as an improvement of the power-matching situation.

Things are not that simple, though – the tube is a **non-linear component** that is only inadequately described by the theory of linear two-ports. Experience shows that it is conducive to distinguish between (approximately) linear and (strongly) non-linear operation. For small drive-levels, the power stages works approximately in a linear fashion♣. In this case the internal impedance of the tubes can be estimated from the slope of the output characteristic. Depending on the type of tube and on the operating point, we can expect an internal tube-impedance of 10 – 100 kΩ. If we would now chose – in order to achieve power matching – the load resistor at the plate exactly as big as the internal impedance of the tube (e.g. 100 kΩ), then the AC plate-voltage would have to be 3.1 kV_{ss} in order to reach P = 12 W … no normal tube could withstand that. Equal impedance definitely is not the desired goal; rather, the output power is to be maximized while considering the given limit values. In the chapters on the specific push-pull power stages, we will give guidelines for calculating the optimal load resistor at the plate – typically, values around 1 – 2 kΩ are the result.

♣ Given that a sufficient bias-current has been set in the case of push-pull operation.

The optimal load-resistance for the plate is considerably smaller than the internal impedance of the tube, and therefore the internal impedance of the transformer is considerably larger than the nominal impedance of the loudspeaker. The loudspeaker voltage consequently depends strongly on the loudspeaker impedance. This is not a disadvantage, though, because – in contrast to HiFi-loudspeakers – emphasizing speaker- and enclosure-resonances is not generally undesired in guitar amplifiers. In fact, it is seen as a special sound characteristic and even asked for in many cases. Still, it needs to be considered that the stiff-current-source feature dies a rather sudden death as clipping occurs. The power stage is of high output impedance only while it remains in linear mode; for overdrive, the plate-voltages of the push-pull amplifiers (and therefore the output voltage of the output transformer, as well) hit a relatively rigid border: the residual voltage of the tube (e.g. 50 V). **Fig. 10.5.18** shows the output characteristic of a 6L6-GC in combination with a few internal impedances. Just like any other tube, the 6L6 does not have one single internal impedance. Rather, the latter is strongly dependent on the drive-signal level, and it changes by up to two orders of magnitude as the operating point shifts. The tube will be of high impedance (about 70 kΩ) in the range of usual bias currents (e.g. 350 V, 30 mA), but become of lower impedance at the overdrive-limit (e.g. 50 V, 200 mA). Of course, this is not really that surprising because the tube is a strongly non-linear component. We need to always remain aware of this, especially since the theory of LTI-systems with its relatively simple calculation methods is all too alluring – just like it is also deceptive. Connecting a 14:1-transformer to the **6L6-GC** shown in the figure, the transformation will be from 72 kΩ to 367 Ω, which is a high impedance in comparison to an 8-Ω-speaker. The transformer will, however, transform the 2 kΩ to 10 Ω.

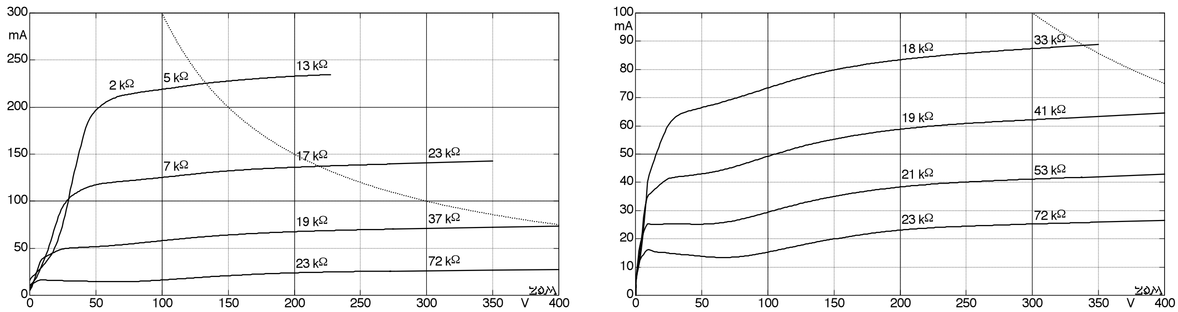

Fig. 10.5.18: Output characteristics of the 6L6-GC, including a few internal impedances. U_{g2} = 300V, R_{g2} = 0.

The internal impedance specified in the **datasheet** of a tube is an orientation-value that may be used for small-signal considerations as a rough approximation. More extensive calculations using it are not advised; first, because the power stage rarely operates under small-signal conditions, and second, because the internal impedance is specific to a given operating point, and on top of that it also depends on the voltage at the screed-grid. For the 6L6-GC, the datasheet specifies an internal impedance of 33 kΩ (class-A). This is a good match to the measurement data given above but remains usable only for very few guitar amplifiers because they normally operate in class-AB-mode. For the latter, datasheets usually do not give any internal impedance – rather, the optimum load impedance is given. This optimum load impedance – and not the internal impedance – may serve to calculate the transformation ratio of the output transformer. To calculate the source impedance R_Q (as it is "seen" by the speaker) for class-AB operation, several peculiarities need to be considered. For small drive levels, the two power tubes cooperate and R_Q is halved: with a 10:10:1 transformer, we obtain R_i = 60 kΩ → R_Q = 300 Ω. For high drive levels, only one tube is active at a time (for each half wave). Moreover, we need to consider that the transformer is not at all ideal, either: R_Q is reduced by the (non-linear!) main inductance and the capacitance of the winding.

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Fig. 10.5.19 shows measurements of a power stage (JTM-45, KT-66, GZ-34). The uppermost curve results from switching-off the supply voltage (Standby): the tubes (with the heater in operation) do not insulate perfectly but are of rather high impedance – transformer-capacitance and -inductance determine the impedance. Switching on the supply voltage but keeping the negative feedback deactivated (no NFB) reduces the internal impedance R_Q because the tubes are now operated in the operating point. As we switch on the negative feedback, R_Q experiences another, very pronounced drop. Since the frequency response of the feedback loop can be modified by the Presence potentiometer, various characteristics may be realized. The strong resonance peak at 7 kHz is due to phase-shifts caused by the presence-filter (low-pass within the negative-feedback loop, see also Chapter 10.3.3). The increase in the no-NFB-condition does not happen proportionally to the frequency: this is due to the non-linear main inductance that depends on the drive levels, and on the operating point within the hysteresis (Chapter 10.6).

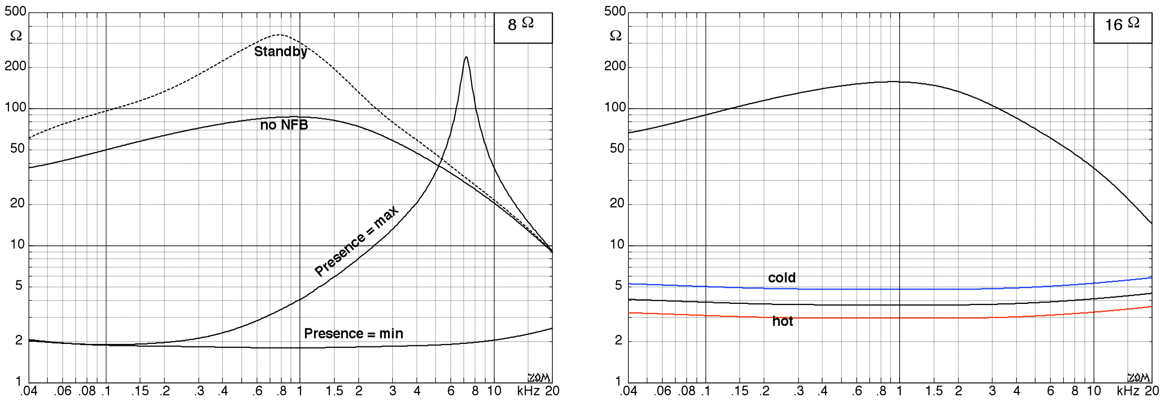

Fig. 10.5.19: Internal impedance of the JTM-45-power-stage. Left for the 8-Ω-output, right for 16 Ω. The right-hand picture also shows the effect of the bias on the internal impedance.

The impedance also depends on the bias-current of the power tubes, and on the power-tube type. If the power tubes are not equal, pre-magnetization effects of the transformer core weigh in, as well. Because of these dependencies, it is advisable to take from Fig. 10.5.19 not more than the fact that output impedances around 100 Ω occur without negative feedback. Any exact data or frequency responses would be too much connected to the individual amplifier. On the other hand, taking into account that normally the feedback-loop in the KTM-45 is closed, the differences in regular operation may not be that big, after all. With closed NFB-loop, we see an astonishingly small internal impedance (= magnitude of the output impedance) of the power stage of merely 2 Ω (for the 8-Ω-output). This power amp does have efficient NFB! Well, that's the case at least if we don't turn up the Presence-control too much … Who would have though that Marshall (not actually known for any HiFi-designs) would decrease the output impedance via negative feedback (that will decrease distortion) to values that are significantly below the load impedance!

At Marshall, this take on things would not always remain, as the 18-W-amp developed later proves. Its two EL84's operate in a power stage that entirely does without any negative feedback. VOX immediately comes to mind, but allegedly the "Watkins Dominator" was the inspiration for Ken Bran [Doyle]. Still, there are no big differences to the AC-30 with regard to the internal impedance, as Fig. 10.5.20 shows. Also generally valid: such measurement logs are snapshots – every tube-swap will change the amplifier-parameters and as such also the internal impedance. Chapter 10.5.11 will elaborate on how far selecting the power tubes helps to avoid inter-individual differences. Moreover, the effects of the bias-setting are discussed in Chapter 10.5.8.

Of the output-impedances documented in **Fig. 10.5.20**, three are taken from power stages that do not include negative feedback: VOX AC-30, Marshall 18W and Tweed Deluxe; the Super-Reverb does have NFB but was additionally measured with open negative-feedback loop.

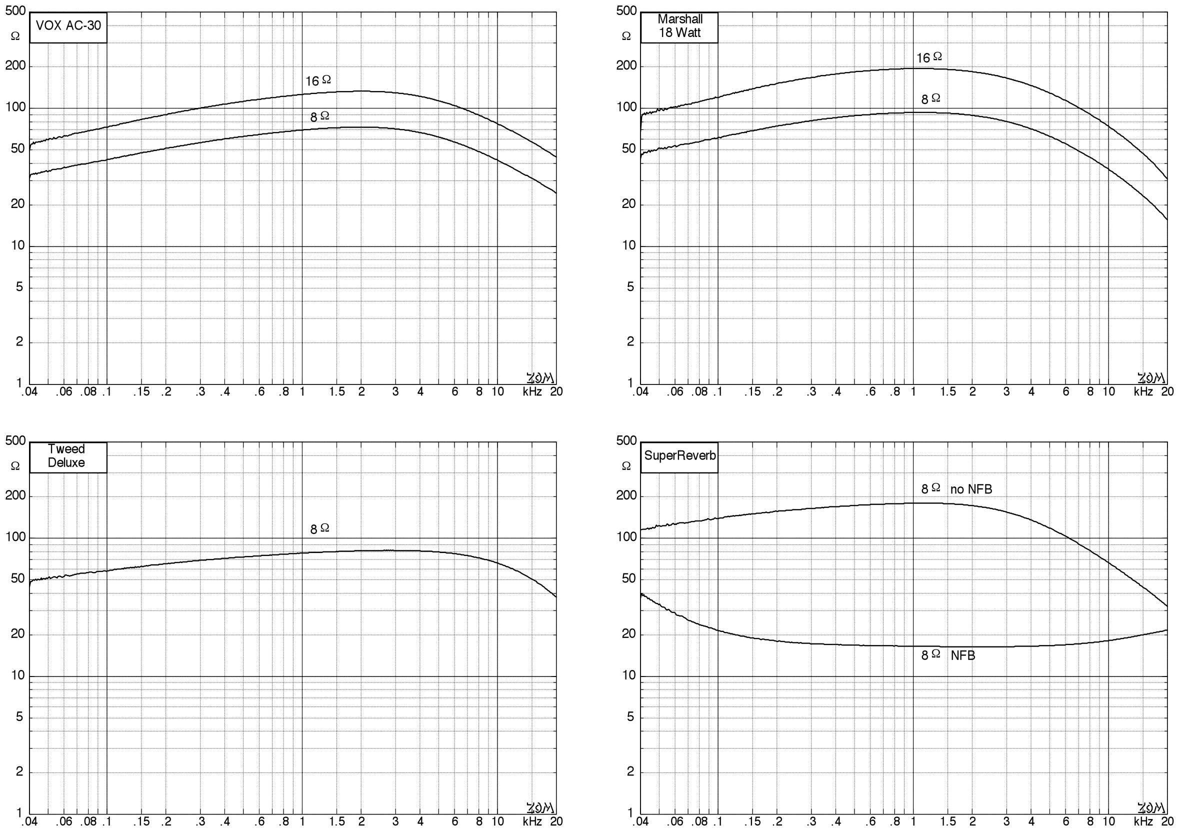

Fig. 10.5.20: Internal impedances of several guitar amplifiers (Super-Reverb with and w/out negative feedback).

In view of these significant internal impedances, we could ask where the **energy** necessary for their operation is actually sourced. If an 8-Ω-resistor absorbs 30 W and if it has serially connected an impedance of 75Ω (the internal impedance of the amplifier), will the latter then absorb 281 W? Is that why the VOX gets so hot? No – with this thinking, we would in fact abuse a model. *With respect to a specific given problem, an equivalent circuit shows the same behavior as the real structure* [20]. In our case, however, the given problem (the real source and its replacement by an ideal source including an internal impedance) is not the energy balance. Rather, the difference between source voltage and terminal voltage is to be illustrated. We see this right away as we replace the voltage source (with a serially-connected internal impedance) by a current source (with a parallel-connected internal impedance): with open terminals, the internal losses for the current source are at a maximum, and zero for the voltage source. The model of a source with internal impedance is well equipped to explain the dependency of the output voltage on the load impedance (loudspeaker impedance): for a low-impedance source, the terminal voltage is practically independent of the load, while for a high-impedance source, the terminal voltage is practically proportional to the load impedance. Model and reality are a good match for visualizing the given problem. However, the model is not suitable to determine dissipation power in tubes: the actual (real) voltages and current in the tubes need to be considered for this.