10.7.2 The charging circuit

In tube amplifiers, the typical supply-voltage lies in the range of 200 – 500 V DC. The mains transformer can only deliver AC and therefore a rectifier is required. Older guitar amplifiers mostly include a tube rectifier while newer ones often (but not always) sport a silicon rectifier. The main difference is that a tube rectifier necessitates a filament heating while Si-rectifiers do not. Moreover, the Si rectifier will generate a voltage drop of about 1 V in the flow-direction while this will amount to 40 V or more in a tube rectifier.

In most guitar amplifiers, both halves of the sine wave are rectified, this approach being termed a two-way or **full-wave rectifier**. The two secondary voltages generated by the transformer are in opposite phase so that each of the two rectifier-diodes conducts only during one half-wave (**Fig. 10.7.2**). However, this does not happen during the complete half-wave but only close to the maximum voltage, because the supply-voltage generated at the cathodes of the diodes is smoothened by an electrolytic filter capacitor. From an idealized point of view, the diode will only conduct if the anode/plate-potential (at the transformer) is higher than the cathode-potential (at the capacitor). With none of the diodes conducting, the capacitor-voltage will decrease exponentially: $u = \hat{u} \cdot \exp(-t/\tau)$; here, τ is the time-constant given by the capacitance and the load-resistor, e.g. τ = 32 µF · 2000 Ω = 64 ms. If this time-constant is large relative to half the cycle-duration, there will be only a small voltage decrease, and the current through the diode will flow only during a short time (small **angle of current flow**). It follows according to the law of charge-conservation, that the peak current will be the higher the smaller the angle of current flow is.

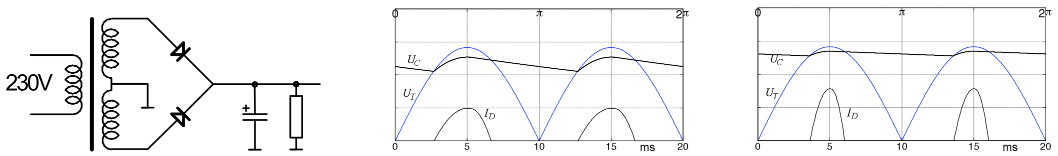

Fig. 10.7.2: Full-wave rectifier. Voltages and currents for two different angles of current flow.

In strongly simplified terms: if, given a load current of 200 mA, a current is flowing through the diodes only during 1/5th of the time, then this current needs to be five times as strong as the load current i.e. 1 A. In reality, load- and diode-currents can only be described with relatively complicated formulas, but the factor five mentioned here is a good benchmark. If a power supply is designed for 400 V / 100 mA, a peak current of 1 A may flow through the diodes. This peak current is specified in extended datasheets – in the abbreviated versions, however, only an allowable average current value is given. In the above example, this average is 100 mA per diode. The following **table** indicates both the peak current $\hat{\imath}$, and the average I_{DC} for a number of diodes. For the tube diodes, I_{DC} is the load-current (all listed rectifier tubes are *double*-diodes), while for the Si-diodes, I_{DC} is the average current per diode. Also included is the **internal impedance of the transformer** R_{Tr} (per secondary winding). Together with the capacitance C_L and the load resistance R_L, this impedance determines the actual peak current $\hat{\imath}$. If R_{Tr} is made too small, of if C_L is too large, the rectifier tube may be overloaded under certain conditions! Normally, R_{Tr} cannot easily be changed – transformers are mostly picked on the basis of their power. If the value of R_{Tr} turns out to be too small, the simple solution is to connect a resistor in series! The given maximum capacitance values are taken from the datasheet of the manufacturers, and a bit of modesty is called for here: if we install – in order to further reduce the remaining ripple – a 100-µF-cap instead of the permitted 32 µF, then the tube will be operated outside of its specifications. Depending on the quality, it will hold up for some time – or not.

Type	Filament	U_{Tr} / V_{eff}	$\hat{u}$ / V	I_{DC} / mA	$\hat{\imath}$ / mA	C_L / µF	R_{Tr} / Ω
EZ80 (= 6V4)	6,3 / 0,6	2 x 350	1000	90	270	50	2 x 300
5Y3-GT	5,0 / 2,0	2 x 350	1400	125	440	10	2 x 50
EZ81 (= 6CA4)	6,3 / 1,0	2 x 350	1000	150	450	50	2 x 240
5V4-G	5,0 / 2,0	2 x 375	1400	175	525	10	2 x 100
5U4-G	5,0 / 3,0	2 x 450	1550	225	800	32	2 x 75
5AR4	5,0 / 1,9	2 x 450	1700	225	825	40	2 x 140
GZ34	5,0 / 1,9	2 x 350 2 x 450 2 x 550	1500	250 250 160	750 750 750	60 60 60	2 x 75 2 x 125 2 x 175
5U4-GB	5,0 / 3,0	2 x 450	1550	275	1000	40	2 x 67
83 (Hg-vapor)	5,0 / 3,0	2 x 450	1400	250	1000	40	2 x 50
BYX 90	–	2 x 2kV	7500	0,55 A	5 A	♠	♠
1N 4007	–	2 x 300	1000	1 A	10 A	♠	♠
BY 133	–	2 x 390	1300	1 A	10 A	♠	♠
1N 5399	–	2 x 300	1000	1,5 A	10 A	♠	♠
1N 5062	–	2 x 240	800	2 A	10 A	♠	♠
BY 255	–	2 x 390	1300	3 A	20 A	♠	♠
1N 5408	–	2 x 300	1000	3 A	20 A	♠	♠

Table: Operational data of mains-rectifiers (from datasheets; please consider manufacturer-specific details!) For silicon-rectifiers (♠), the internal impedance of mains transformers are normally always big enough, and the maximum load-capacitance does not represent any constraint, either, at (typically) > 200 µF.

The elaborations above have shown that in the charge circuit – between transformer, rectifier and filter capacitor – a **peak current** of 1 A can easily flow. Multiplying this value with a resistance of 1 mΩ yields a voltage drop of 1 mV. For a 0.5-mm-wire, 1 mΩ is reached already with a length of about 1 cm – this merits some consideration: if we contact the ground-conductor of the charge circuit at *two* different points that are 1 cm away from each other, a potential-difference of 1 mV is generated. For an input of high sensitivity, the full-drive input-voltage is in the same order of magnitude! Of course, the capacitor connections also have a non-negligible resistance, but here it is only the ripple that is marginally increased. If, according to the motto "ground is ground", the input-socket ground is connected to one point of the filter-cap feed, and the input of the pre-amplifier not to the same point but to another one off by 1 cm, severe **hum-interference** is bound to occur.

It is recommended for the wiring of an amplifier to draw up a plan in which all ground-wires are shown as resistors – this gives a good idea about unwanted voltage drops. By the way, similar problems may pop up in the secondary circuit of the output transformer, because here, too, the current may reach several Amperes. Therefore note: connect the output transformer directly to the output-socket; avoid channeling the loudspeaker current through the amp chassis.

In the following, **measurements** taken from amplifier power-supplies will be introduced – a *calculation* would be possible, as well, but requires a lot of effort because both the mains transformer and the rectifier are non-linear components. As a first example, we will look into the power supply of the TAD-Deluxe kit. It uses the **5Y3-GT** as a rectifier tube; according to the datasheet, it has to make do with a 10-µF-filter-cap. For the measurements, this filter-cap was loaded with 10, 5 and 3 kΩ – the corresponding charge-current amounts to 45, 85, and 130 mA, respectively, and the peak current through the diodes amounts to 180, 280, and 380 mA, respectively (**Fig. 10.7.3**).

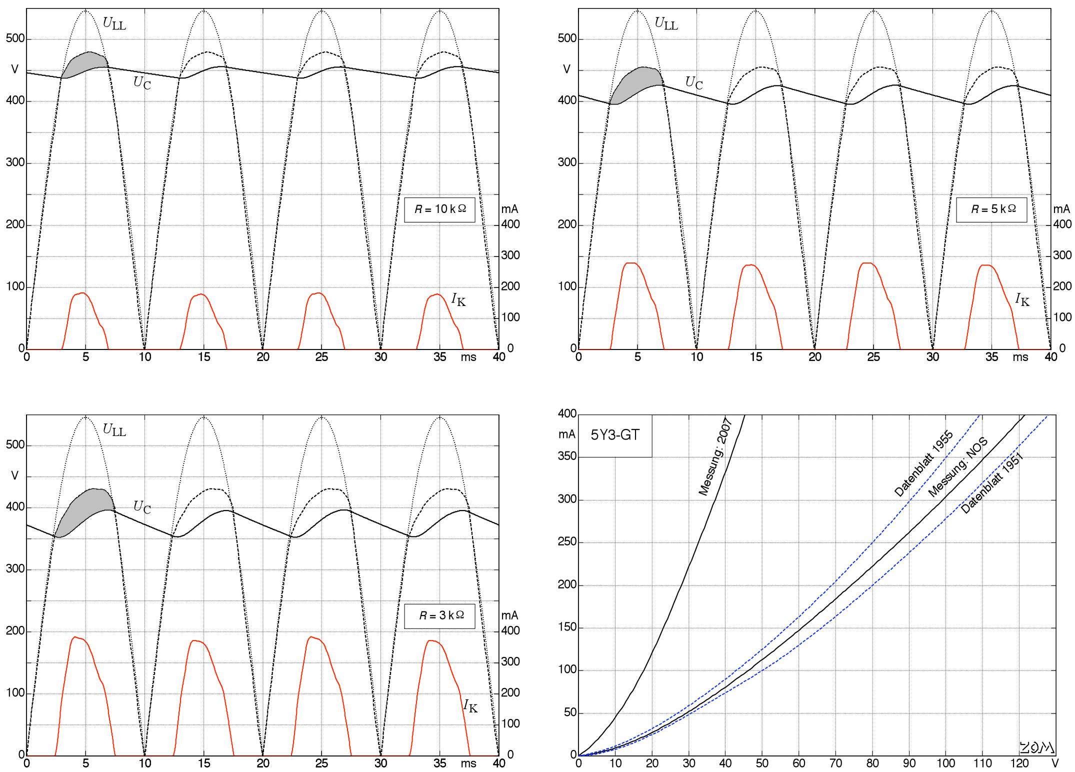

Fig. 10.7.3: TAD-Deluxe: voltages and currents for the full-wave tube-rectifier; C_L = 10 µF.

As is easily seen, the relationship of peak-current to average current is no bigger than a factor of 2 – mainly due to the mains transformer at work here. Its secondary windings have a DC-resistance of 225 Ω, and thus the voltage breaks down strongly under load, and the angle of current-flow is relatively large. The thin line in the figure belongs to the open-loop transformer-voltage; depicted below it is the voltage under load. The voltage across the filter cap oscillates up and down in the shape of a saw-tooth wave; the forward-voltage of the tube is highlighted in grey. For the measurements, a rectifier tube of recent production was used; it shows a voltage drop in flow-direction of 30 – 40 V. In the U/I-diagram, two old datasheet-curves are entered with a dashed line, and in addition a measurement curve taken with an RCA NOS tube. **NOS = new old stock**: this designates tubes that have been remained unused on the shelf for decades, and which now are deployed for the first time. A tube with a voltage-drop of more than 100 V in the flow direction will indeed help the amplifier to a different operational behavior: the supply-voltage collapses even further than shown in Fig. 10.7.3. If this “sagging” is, in fact, desired, but no NOS-tube is available: a 200-Ω-resistor will do the same job.

 Translated by Tilmann Zwicker

The curves shown in Fig. 10.7.3 indicate that the data of a tube-type may not be simply taken from *one* datasheet. First, there are manufacturer-specific idiosyncrasies, and second, the production methods were always subject to an ongoing change. On the other hand, the almost inflationary multitude of designation letters (5Y3-G, -GT) often merely refers to differences in the glass container and not to electrical data. From this point of view it may be justified to ask horrendous prices for certain old tubes – tubes from today's production indeed do have different data. However: there are reports that it may be very easy to have any desired tube replicated even in relatively small numbers by the gentleman with the name consisting of merely two letters♣. At least as far as the cosmetics are concerned: perfect! Even the old GEC-sticker is superbly imitated. Okay … the electrical data … well, you can't have everything, can you? Back to the roots … or to revenue. Revenue, mostly, though, 'cause the NOS-tube built for 5 $ can easily be sold for 50 $ via the internet (*foun in grandads atic no garratee*). The odd tube will bring in excess of 500 $ – here the financial suffering alone will automatically take care of an "unparalleled sound experience". At least for rectifier tubes, such escapades are not required from the point-of-view of physics: any characteristic may be approximated with a few diodes and a few resistors.

Apart from manufacturer-specific and vintage-specific differences, **manufacturing scatter** within one lot also occurs, and so the luxury-tubes are individually measured i.e. **selected**. If you order selected tubes and they are delivered without a "selected" label, you can complain. You cannot complain if you receive tubes that are not selected. That is because "selected" merely indicates that the tube is labeled "selected". Whether, and how, a selection process happens – that mostly remains in the dark realm of trade secrets. Two "selected" GZ-34 acquired from a German tube distributor both were defective. How is something like that possible? A broken glass-container would be understandable – that can happen post-selection. But too low a power-capacity? That *had* to stand out during selection – because the label reads, after all: **GZ34-STR Selected**. How can anyone select without testing <u>each</u> tube? Only the third specimen of this supplier could deliver the current customary for a GZ34. This is in sharp contrast to the unselected Ultron-tubes: each of the three acquired tubes was perfect. **Fig. 10.7.4** shows measurement diagrams taken from "selected" GZ34's. RC-loading was 32 µF, the load current was 200 mA. The high-quality tube (A) has both systems operating with almost identical characteristic while the other two tubes (B/C, D/E) are expensive rejects.

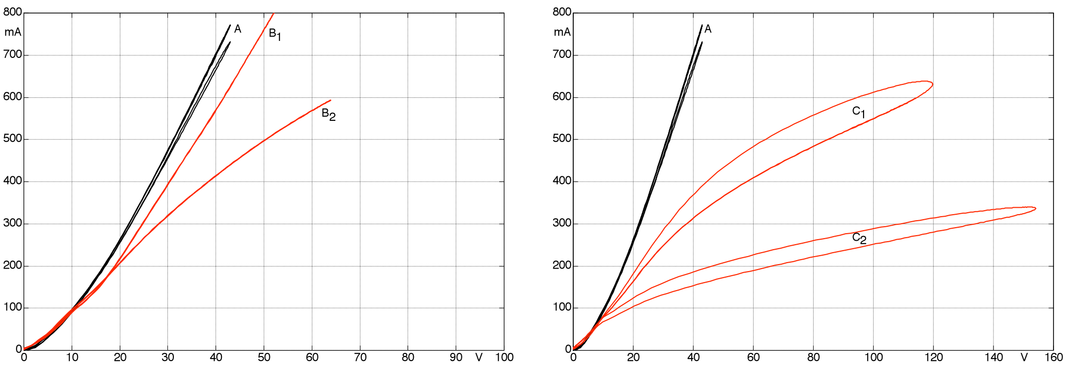

Fig. 10.7.4: GZ34 (full-wave rectifier). U/I-characteristic of "selected" tubes of varying quality.
A = tube o.k. B_1 and B_2 designate the two systems of a bad tube; C_1 and C_2 belong to a very bad tube the characteristic of which changes from bad to very bad within a few seconds.
[badly coated cathodes ⇒ Schade, O.: Analysis of rectifier operation, Proc. IRE, July 1943, 341-361].

♣ The RCA-tube measured in Fig. 10.7.3 was not sourced there - it could be located in the basement of the author's home.

